

NUCLEAR INSTRUMENTS & METHODS

A JOURNAL ON ACCELERATORS, INSTRUMENTATION
AND TECHNIQUES IN NUCLEAR PHYSICS

EDITOR: K. SIEGBAHN - UPPSALA

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NUCLEAR INSTRUMENTS AND METHODS

A journal on accelerators, instrumentation and techniques in nuclear physics

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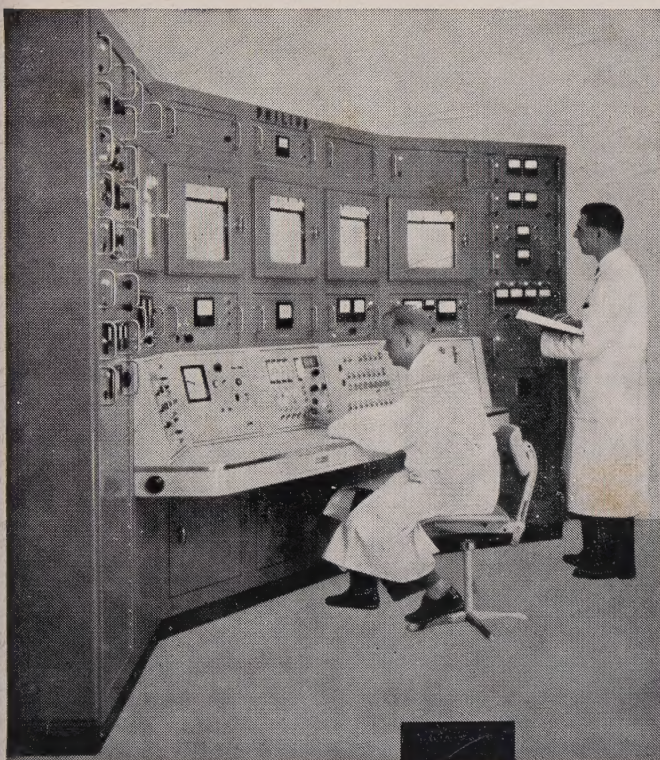
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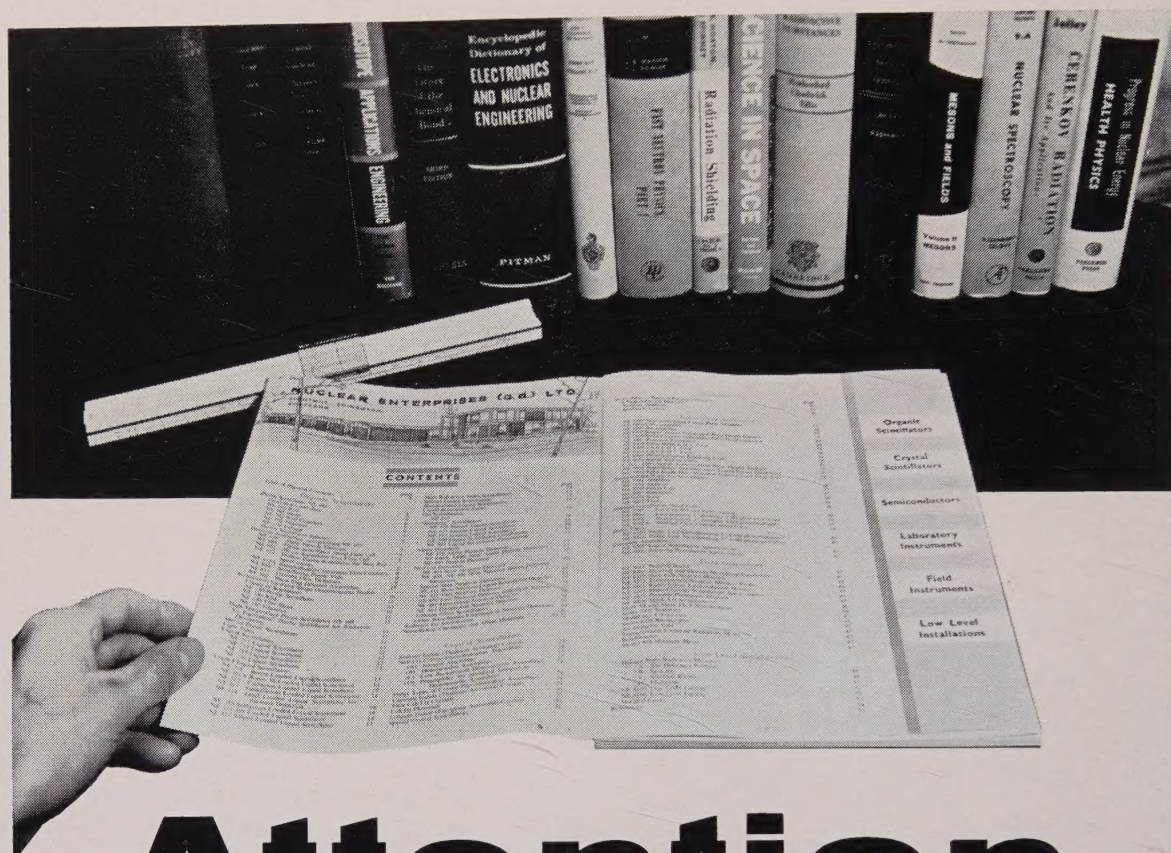
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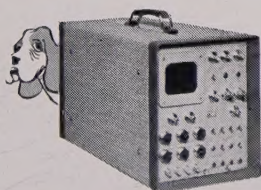
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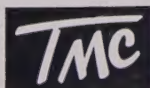
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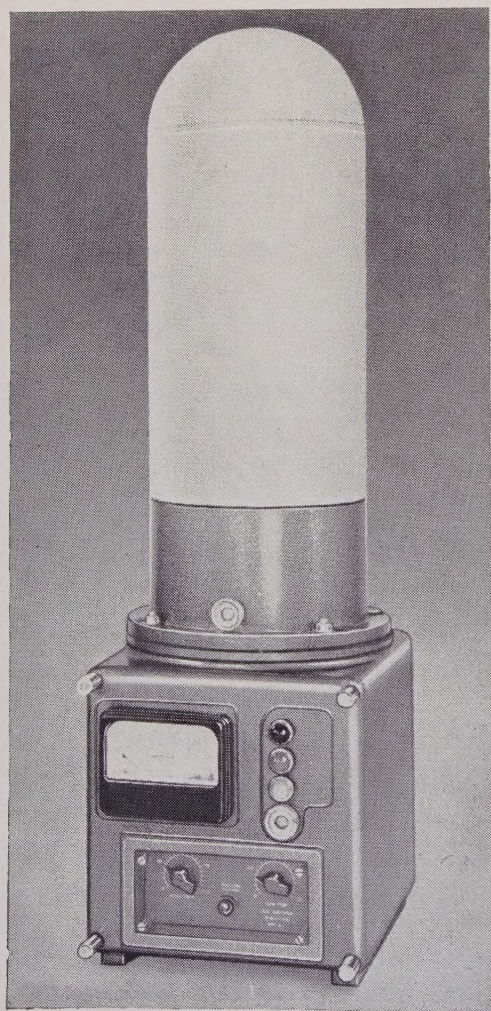
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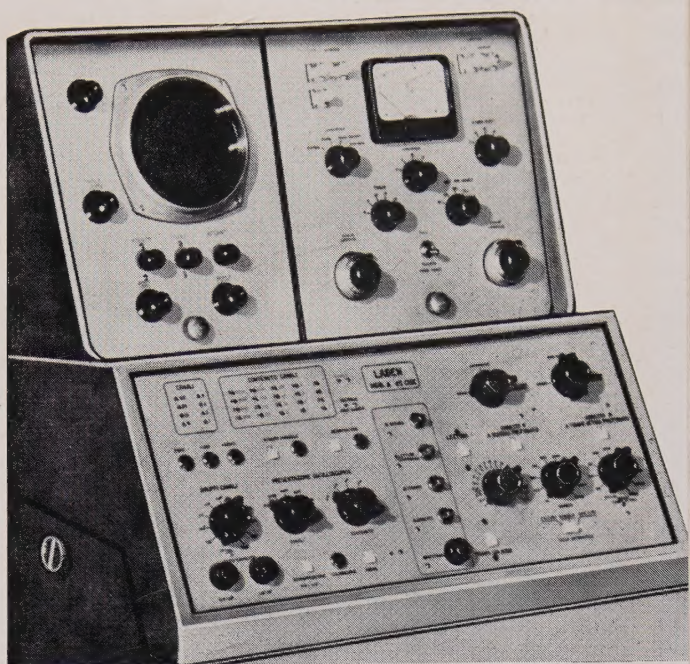
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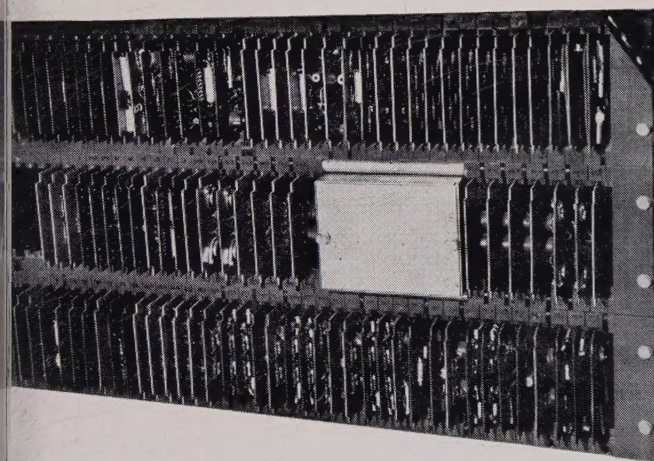


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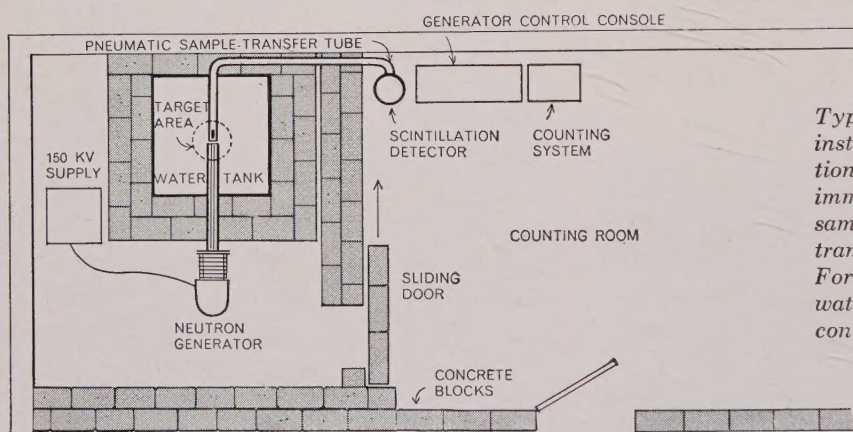
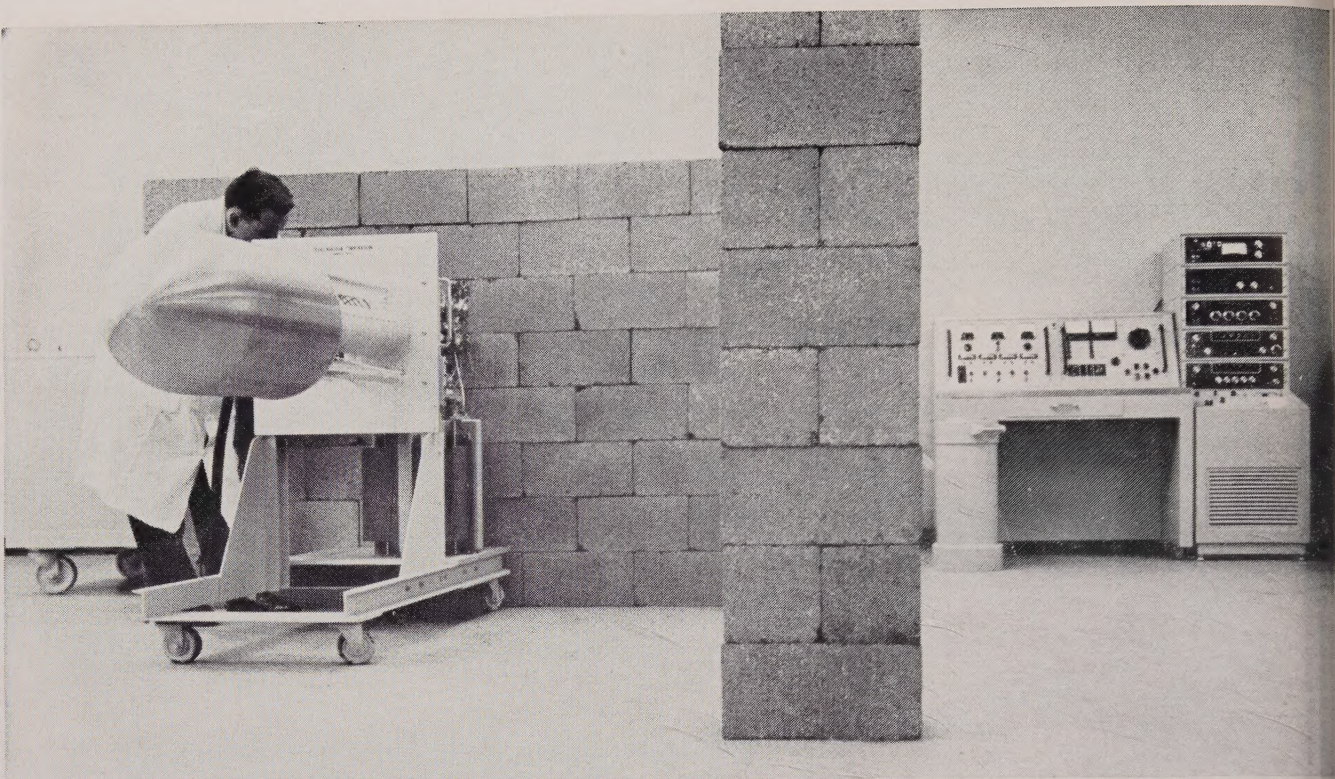


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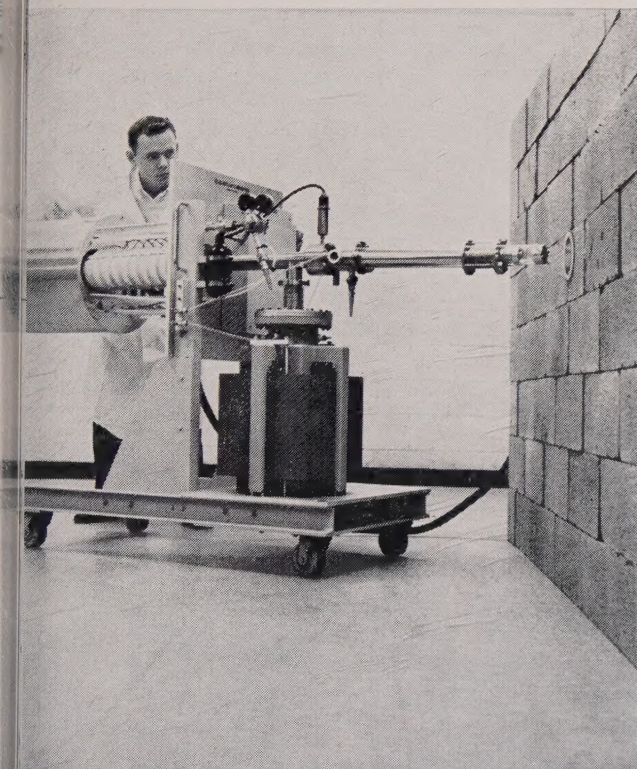
Typical neutron generator/counting installation. For fast-neutron activation, a "dry well" (dotted line) is immersed in the water tank, and the sample contained in the pneumatic transfer tube is suspended in air. For thermal-neutron activation, the water surrounds the pneumatic tube containing the sample.

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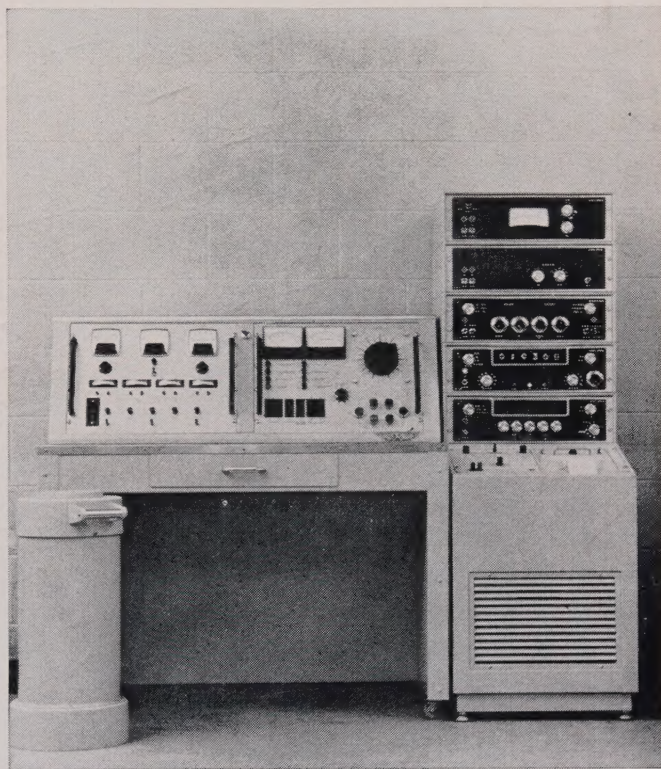


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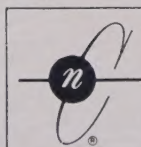
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Instrumentation for measurement of gamma radiation. At the left of the console is a scintillation detector connected with the target area by the pneumatic sample-transfer tube. At the right is automatic gamma spectrometry instrumentation.



with the scintillation detector and counting instrumentation shown.

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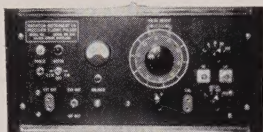
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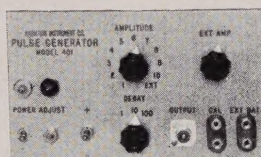
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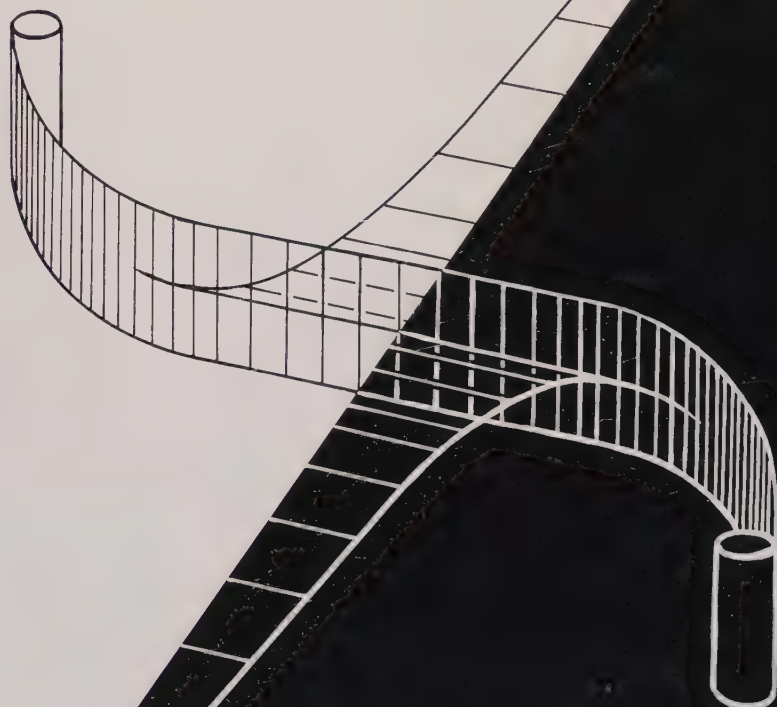
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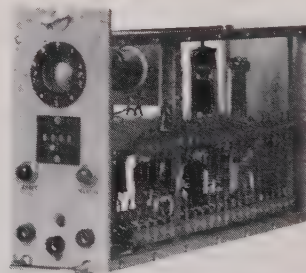
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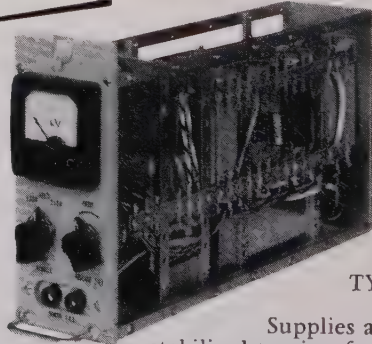
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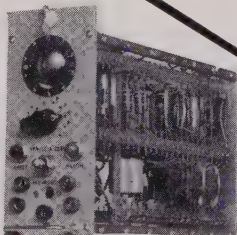


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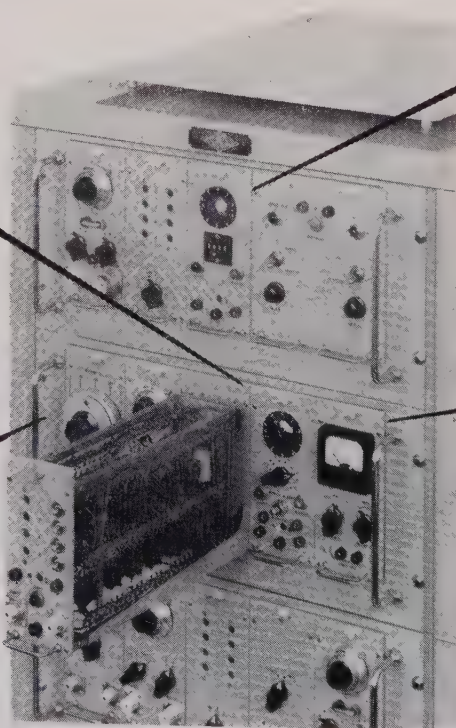
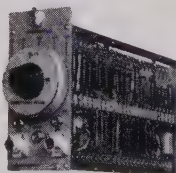
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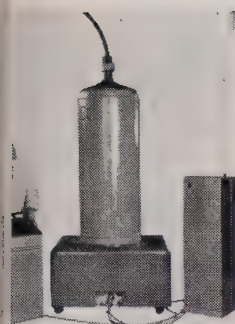


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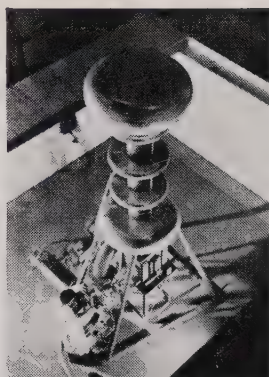
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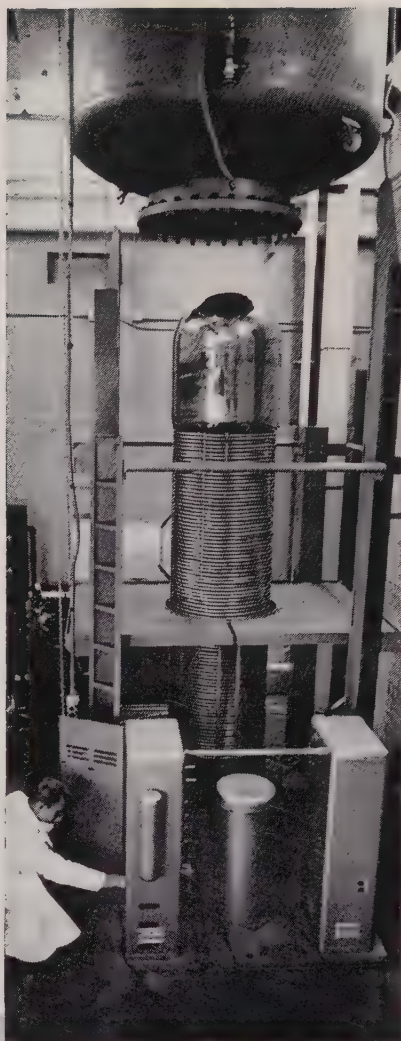
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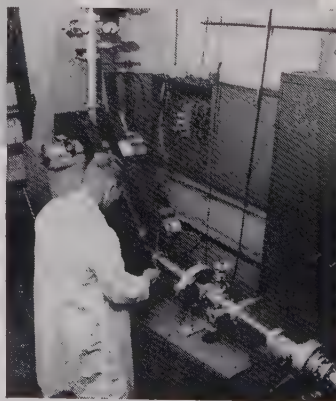
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J. VAN BLADEL

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Department of Electrical Engineering, University of Wisconsin, Madison 6, Wisconsin

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A comparison is made between the electromagnetic fields in a circular accelerator and in the linear accelerator obtained by “unwrapping” the circular structure. In both cases the fields are excited by a narrow gap perpendicular to the axis, and across which a constant radio-frequency voltage is applied.

Introduction

Circular accelerators of the type shown in fig. 1 are often excited by a radio-frequency voltage applied across a narrow radial gap g . A typical method to generate this voltage consists of incorporating the gap into a surrounding resonant cavity, which is then excited at one of its resonant frequencies. The resonance

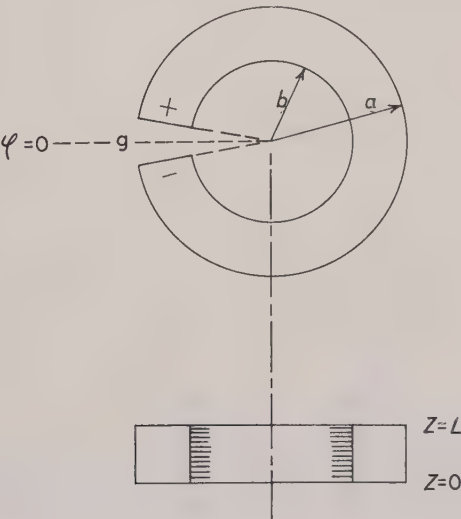


Fig. 1. Circular accelerator with radial gap.

phenomenon creates a large voltage across the gap. The resonant mode is commonly chosen to yield a practically constant voltage (in phase and amplitude) all along the gap contour. The tangential electric field in the gap will, in these circumstances, be described by the formula

$$E_t = \frac{V}{r} \delta(\varphi) u_\varphi \tag{1}$$

where u_φ is a unit vector in the direction of increasing azimuth φ . It is our purpose to calculate the fields inside the “doughnut” volume for such a field configuration. Furthermore, it is our intention to in-

† AEC Research and Development Report. Research supported by the U.S. Atomic Energy Commission, Contract No. AT(11-1)-384.

investigate the validity of the approximation in which the circular accelerator is replaced, locally at least, by a straight duct of identical cross-section. This simplification results in the replacement of the circular accelerator of fig. 1 by the rectangular wave-guide of fig. 2, excited by a periodic array of gaps. The spacing between gaps must be equal to the average length of a circular path. The field in the gap now becomes

$$E_t = V\delta(y) u_y. \quad (2)$$

It is our goal to calculate the fields in the linear accelerator, and to compare them to those of the circular accelerator of similar cross-section. Our final purpose will be to get an idea of the error committed by neglecting the curvature of the vacuum chamber.

2. Fields in the Circular Accelerator

The accelerator of fig. 1 is nothing but a coaxial cavity with a given impressed tangential electric field across its boundary surface. The fields inside such a cavity can be calculated from a knowledge of the resonant modes, which can be written down explicitly for the coaxial geometry¹). The relevant formulae can be found in the literature²), and will not be reproduced here. Alternatively, the accelerator can be looked at as a coaxial wave-guide with given tangential electric field across its cylindrical wall and terminal flanges. Both approaches very naturally yield the same results. The second approach, which is perhaps less classical but more concise, is presented in some detail in the appendix. We only wish to quote the final results here. The formulae involve the following two kinds of basic functions:

(a) Functions $R_m(\mu_{mp}r)$, linear combinations of Bessel and Neumann functions vanishing at the inside and outside radii.

$$R_m(\mu_{mp}r) = J_m(\mu_{mp}r) + A_{mp}N_m(\mu_{mp}r)$$

where A_{mp} and μ_{mp} are determined by equations

$$\frac{J_m(\mu_{mp}b)}{N_m(\mu_{mp}b)} = \frac{J_m(\mu_{mp}a)}{N_m(\mu_{mp}a)} = -A_{mp}. \quad (3)$$

(b) Functions $S_m(v_{mp}r)$

$$S_m(v_{mp}r) = J_m(v_{mp}r) + B_{mp}N_m(v_{mp}r)$$

the first derivative of which vanish at the inside and outside radii.

$$\frac{J'_m(v_{mp}b)}{N'_m(v_{mp}b)} = \frac{J'_m(v_{mp}a)}{N'_m(v_{mp}a)} = -B_{mp}. \quad (4)$$

Tables of roots of (3) and (4) are very sketchy, and a program to compute the latter on an IBM 704 was written by Dr. J. McNall. With the help of these functions the formulae for the three components of the electric field read as follows:

$$\begin{aligned} \vec{E}_r = V \sum_m \sum_p \left\{ \frac{m}{\pi \mu_{mp}^2} \sin m\varphi \frac{dR_m}{dr} \frac{\sinh \gamma_{mp}z + \sinh \gamma_{mp}(L-z)}{\sinh \gamma_{mp}L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \right. \\ \left. - \frac{m}{\pi v_{mp}^2} \sin m\varphi \frac{S_m}{r} \left[\frac{v_{mp}^2}{\tau_{mp}^2} - \frac{k^2 [\sinh \tau_{mp}z + \sinh \tau_{mp}(L-z)]}{\tau_{mp}^2 \sinh \tau_{mp}L} \right] \frac{S_m(v_{mp}a) - S_m(v_{mp}b)}{\int_b^a S_m^2 r dr} \right\} \quad (5a) \end{aligned}$$

¹) See, for example, C. G. Montgomery, *Technique of Microwave Measurements* (McGraw-Hill Book Co., 1947) Ch. 5.

²) J. C. Slater, *Microwave Electronics* (Van Nostrand and Co., New York, 1950) Ch. 4.

$$\begin{aligned}
= V \sum_m \sum_p \left\{ \frac{m}{\pi \mu_{mp}^2} \cos m\varphi \frac{R_m}{r} \frac{\sinh \gamma_{mp} z + \sinh \gamma_{mp}(L - z)}{\sinh \gamma_{mp} L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \right. \\
\left. + \frac{1}{\pi v_{mp}^2} \cos m\varphi \frac{dS_m}{dr} \left[\frac{v_{mp}^2}{\tau_{mp}^2} - \frac{k^2 [\sinh \tau_{mp} z + \sinh \tau_{mp}(L - z)]}{\tau_{mp}^2 \sinh \tau_{mp} L} \right] \frac{S_m(v_{mp} a) - S_m(v_{mp} b)}{\int_b^a S_m^2 r dr} \right\} \quad (5b)
\end{aligned}$$

$$= V \sum_m \sum_p \frac{m}{\pi \gamma_{mp}} \sin m\varphi R_m \frac{\cosh \gamma_{mp} z - \cosh \gamma_{mp}(L - z)}{\sinh \gamma_{mp} L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \quad (5c)$$

where the symbols

$$k^2 = \omega^2/c^2, \quad \gamma_{mp}^2 = \mu_{mp}^2 - k^2 \quad \text{and} \quad \tau_{mp}^2 = v_{mp}^2 - k^2$$

have been used. In a similar manner, the magnetic field turns out to be:

$$\begin{aligned}
= j\omega \varepsilon V \sum_m \sum_p \left\{ \frac{m^2}{\pi \mu_{mp}^2 \gamma_{mp}} \cos m\varphi \frac{R_m}{r} \frac{\cosh \gamma_{mp} z - \cosh \gamma_{mp}(L - z)}{\sinh \gamma_{mp} L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \right. \\
\left. + \frac{1}{\pi v_{mp}^2 \tau_{mp}} \cos m\varphi \frac{dS_m}{dr} \frac{[\cosh \tau_{mp} z - \cosh \tau_{mp}(L - z)] [S_m(v_{mp} a) - S_m(v_{mp} b)]}{\sinh \tau_{mp} L \int_b^a S_m^2 r dr} \right\} \quad (6a)
\end{aligned}$$

$$\begin{aligned}
= -j\omega \varepsilon V \sum_m \sum_p \left\{ \frac{m}{\pi \mu_{mp}^2 \gamma_{mp}} \sin m\varphi \frac{dR_m}{dr} \frac{\cosh \gamma_{mp} z - \cosh \gamma_{mp}(L - z)}{\sinh \gamma_{mp} L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \right. \\
\left. + \frac{m}{\pi v_{mp}^2 \tau_{mp}} \sin m\varphi \frac{S_m}{r} \frac{[\cosh \tau_{mp} z - \cosh \tau_{mp}(L - z)] [S_m(v_{mp} a) - S_m(v_{mp} b)]}{\sinh \tau_{mp} L \int_b^a S_m^2 r dr} \right\} \quad (6b)
\end{aligned}$$

$$= -j\omega \varepsilon V \sum_m \sum_p \frac{1}{\pi \tau_{mp}^2} \cos m\varphi S_m \left[1 - \frac{\sinh \tau_{mp} z + \sinh \tau_{mp}(L - z)}{\sinh \tau_{mp} L} \right] \frac{S_m(v_{mp} a) - S_m(v_{mp} b)}{\int_b^a S_m^2 r dr} \quad (6c)$$

3. Fields in the Linear Duct

Expressions for the fields inside the rectangular duct of fig. 2 are available for a structure with a single exciting gap³⁾. The field of an array of gaps can be found by simple superposition of solutions. With

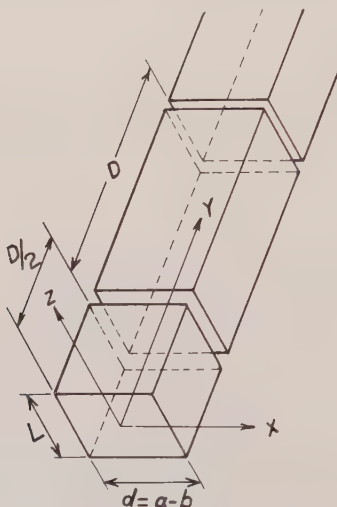


Fig. 2. Linear accelerator with periodic array of gaps.

the parameters indicated in fig. 2, where the $Y = 0$ plane is half way between two gaps, one finds:

$$E_x = \frac{8V}{\pi d} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{n} \sin m\pi \frac{x}{d} \cos n\pi \frac{z}{L} \frac{\sinh S_{mn} \frac{\pi y}{d}}{\sinh S_{mn} \frac{\pi D}{2d}} \quad -\frac{1}{2}D < y < 0 \quad (7a)$$

$$E_y = -\frac{8Vd}{\pi^2} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)} \gamma_{mn}^2}{mn S_{mn}} \cos m\pi \frac{x}{d} \cos n\pi \frac{z}{L} \frac{\cosh S_{mn} \frac{\pi y}{d}}{\sinh S_{mn} \frac{\pi D}{2d}} \quad (7b)$$

$$E_z = -\frac{8V}{\pi L} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{m} \cos m\pi \frac{x}{d} \sin n\pi \frac{z}{L} \frac{\sinh S_{mn} \frac{\pi y}{d}}{\sinh S_{mn} \frac{\pi D}{2d}} \quad (7c)$$

$$H_x = \frac{j\omega\epsilon_0 8Vd}{\pi L} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{m S_{mn}} \cos m\pi \frac{x}{d} \sin n\pi \frac{z}{L} \frac{\cosh S_{mn} \frac{\pi y}{d}}{\sinh S_{mn} \frac{\pi D}{2d}} \quad (7d)$$

$$H_z = \frac{j\omega\epsilon_0 8V}{\pi} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{n S_{mn}} \sin m\pi \frac{x}{d} \cos n\pi \frac{z}{L} \frac{\cosh S_{mn} \frac{\pi y}{d}}{\sinh S_{mn} \frac{\pi D}{2d}} \quad (7e)$$

where

$$S_{mn} = d \sqrt{\frac{m^2 \pi^2}{d^2} + \frac{n^2 \pi^2}{L^2} - k^2}, \quad \gamma_{mn}^2 = \frac{m^2 \pi^2}{d^2} + \frac{n^2 \pi^2}{L^2}.$$

³⁾ J. Van Bladel, J. Appl. Phys. **23** (1957) 1479.

Notice that E_x and E_z are antisymmetric (and the other components symmetric) with respect to the line of the gap.

Longitudinal Energy Kick

Instead of plotting the fields at each point in the vicinity of the gap (a most formidable task indeed, in view of the double infinite sums involved in the formulae for the various components), it is preferable to calculate some "integrated" effects of the fields on the particle trajectories. We start with the energy gain or turn associated with the azimuthal component of the electric field. We shall assume that the radio-frequency is the m^{th} harmonic of the angular velocity of the particle, and write

$$\varphi = \varphi_0 + \Omega t = \varphi_0 + (\omega/m)t.$$

The azimuthal component is of the form $E_\varphi = \sum_v A_v(r, z) \cos v\varphi \cos \omega t$. This gives an energy kick of the form

$$\Delta\epsilon = q \int \mathbf{E} \cdot d\mathbf{s} = \int_0^{2\pi} r A_m \cos m\varphi \cos (m\varphi - m\varphi_0) d\varphi = r A_m \pi \cos m\varphi_0.$$

Introducing the actual value of A_m , taken from (5), one finds:

$$\begin{aligned} \frac{\Delta\epsilon}{\cos m\varphi_0} &= \sum_{p=1}^{\infty} \frac{m^2}{\mu_{mp}^2} R_m(\mu_{mp}r) \frac{\sinh \gamma_{mp}z + \sinh \gamma_{mp}(L-z)}{\sinh \gamma_{mp}L} \frac{\int_b^a \frac{R_m}{r} dr}{\int_b^a R_m^2 r dr} \\ &+ \frac{r}{v_{mp}^2} \frac{dS_m(v_{mp}r)}{dr} \left[\frac{v_{mp}^2}{\tau_{mp}^2} - \frac{k^2 [\sinh \tau_{mp}z + \sinh \tau_{mp}(L-z)]}{\tau_{mp}^2 \sinh \tau_{mp}L} \right] \frac{S_m(v_{mp}a) - S_m(v_{mp}b)}{\int_b^a S_m^2 r dr}. \quad (8) \end{aligned}$$

The quantity $\Delta\epsilon/qV \cos m\varphi_0$, i.e. the transit time factor, is the loss of energy due to transit time effects through the region occupied by the fields. It is plotted in fig. 3 to 6 for a few representative values of the parameters. Parameters of interest are:

(a) The velocity of the particle, as measured by $\beta = v/c$, and which determines Ω and ω . Our plots refer to a value of β constant throughout the cross-section. This means that the radio frequency must be proportional to $1/r$ at the various points to maintain constant velocity ωr .

(b) The geometric dimensions of the vacuum chamber, as measured by the relative curvature $\rho = (a-b)/\frac{1}{2}(a+b)$ and the aspect ratio $\sigma = (a-b)/L$ of the cross-section.

It is, of course, too much labor to cover the whole range of parameters. We have, consequently, restricted ourselves to those values which show relevant trends. One can, for instance, expect the transit time effects 1. to increase with frequency (i.e. with harmonic number m) 2. to increase with penetration of the fields in the vacuum chamber (which will be particularly large, caeteris paribus, for a square cross-section) and 3. to decrease as the particle accelerates. Figure 3 refers to a set of parameters for which all these effects are important, and makes it clear that higher speeds mean a better transit time-factor. Fig. 4 shows that the transit time factor improves when the harmonic number m decreases, and fig. 5 confirms that it also improves with a more elongated cross-section. We have also computed the energy kick for an

accelerator of relative curvature $\rho = \frac{1}{6}$, but the transit time factor for the range of parameters used in fig. 3 to 5 is practically one (with a maximum excursion of 2.5% from that value), and has not been plotted. Fig. 6 gives an idea of the influence of velocity on the transit time factor.

The effect of curvature is apparent in the lack of symmetry of the curves of constant $\Delta\varepsilon$ with respect to

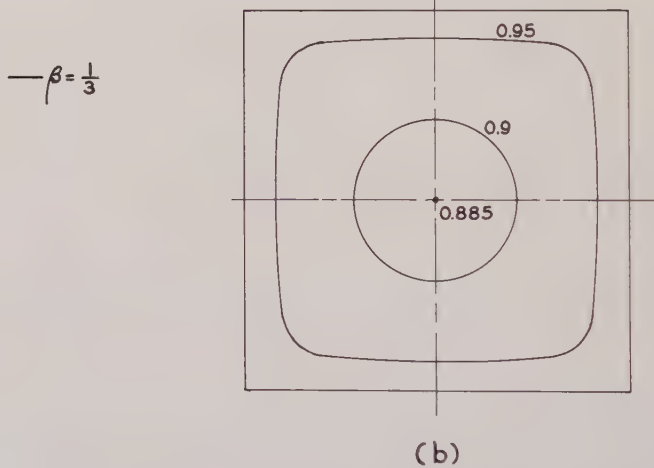
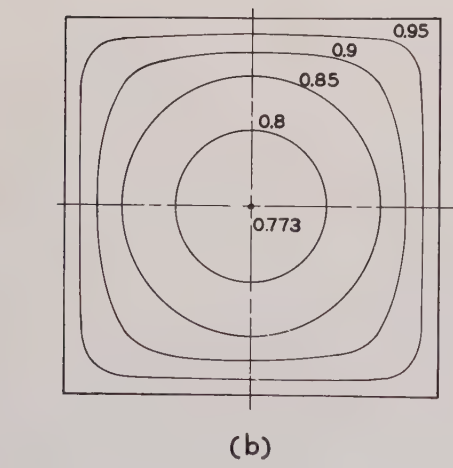
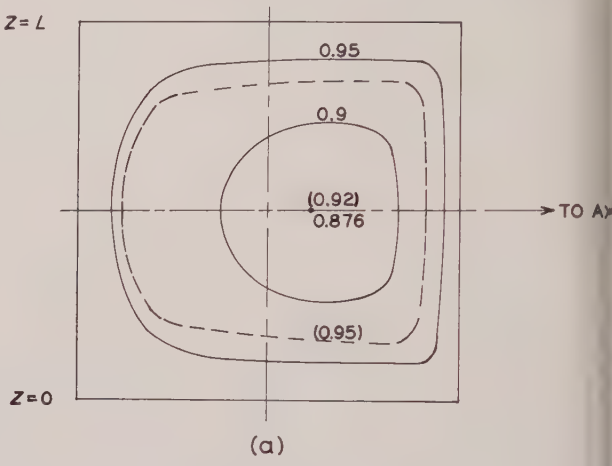
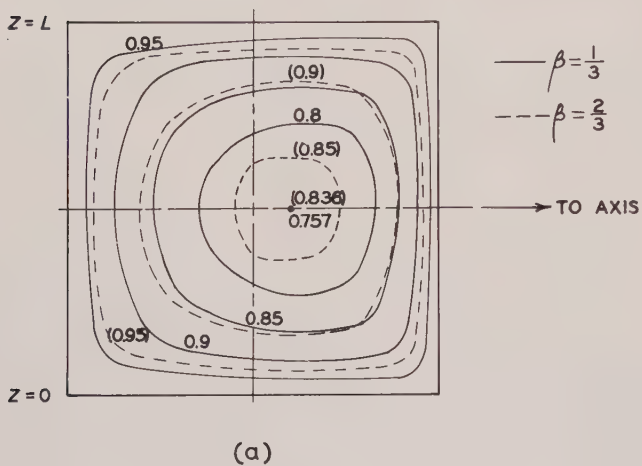


Fig. 3. Distribution of the transit time factor throughout the cross-section for $\rho = \frac{2}{3}$ and a square cross-section (i.e. $\sigma = 1$) for (a) the circular accelerator (b) the linear accelerator. The gap is excited on the third harmonic of the angular velocity, and velocities $\frac{1}{3}c$ and $\frac{2}{3}c$ are considered. For a velocity equal to c , the factor is practically equal to one.

Fig. 4. Transit time factor in the same conditions as in fig. 3, except that the gap is excited on the second harmonic.

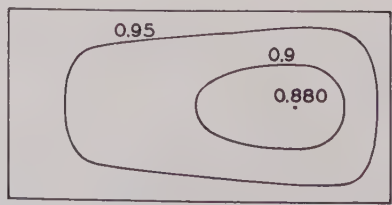


Fig. 5. Transit time factor for a circular accelerator in the same conditions as in fig. 3, except that the cross-section is rectangular with aspect ratio two.

center of the cross-section, and is evidenced by a general shift toward the center of curvature. In the linear accelerator of fig. 2, the energy kick from gap to gap would be, for a particle following a trajectory

$$y = v(t - t_0) \quad (\text{with } t_0 = \varphi_0/\omega)$$

where y is counted from the gap:

$$\frac{\Delta \varepsilon}{qV \cos \varphi_0} = -\frac{16}{\pi^2} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{mn} \frac{\cos m\pi \frac{x}{d} \cos n\pi \frac{z}{L} (\gamma_{mn} d)^2}{S_{mn}^2 + \left(\frac{kd}{\beta}\right)^2} \left\{ 1 + \frac{kd \sin \frac{kD}{2\beta}}{\beta S_{mn} \cosh S_{mn} \frac{D}{2d}} \right\}. \quad (9)$$

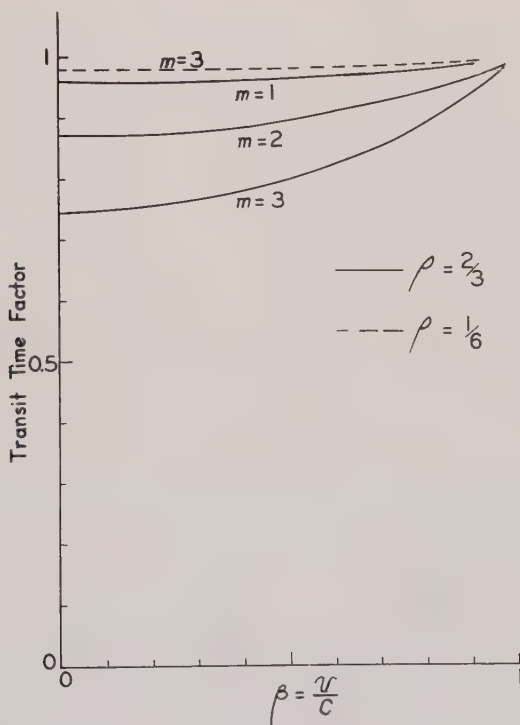


Fig. 6. Transit time factor as a function of velocity for a circular accelerator of square cross-section. The particle is at the center of the cross-section.

A comparison with the transit time factors of the circular accelerator is given in figs. 3 and 4, where the distance D between gaps in the linear accelerator was taken to be the length of the average circle of the corresponding circular accelerator. More precisely, we took D to be $2\pi\rho d = 2\pi\rho(a - b)$. The resulting graphs show that the worst transit time factors are almost the same in the two cases considered, but that the effect of curvature has been to shift their location toward the axis.

Lateral Electric Forces

The radial and z components of the electric field, as given in eq. (5), add up to a term of the form

$$\sum E_v(r, z) \sin v\varphi \cos \omega t,$$

A particle travelling on a circle, its azimuth given by $\varphi = \varphi_0 + (\omega/m) t$, will be subjected to a lateral electric force

$$q \sum E_v \sin \left(v\varphi_0 + \frac{v}{m} \omega t \right) \cos \omega t = \frac{1}{2} q \sum E_v \sin \left[v\varphi_0 + \left(\frac{v}{m} + 1 \right) \omega t \right] + \frac{1}{2} q \sum E_v \sin \left[v\varphi_0 + \left(\frac{v}{m} - 1 \right) \omega t \right]. \quad (10)$$

The various terms of this force are oscillatory in nature, and their angular frequencies are given by $\{ (v/m) \pm 1 \} \omega$. One of these frequencies could very well coincide with a betatron frequency. Also, notice that a time-independent force arises from the term $v = m$. For these and other reasons, a knowledge of $E_v(r, z)$ would be highly desirable for a whole range of geometric parameters and values of v . Explicit formulae for E_v can easily be deduced from eq. (5), and will not be reproduced here. The corresponding quantities for the straight tube can be calculated in a similar fashion. The transverse electric field in that tube is of the form

$$E_{tr} = \sum_m \sum_n f_{mn}(x, z) \sinh \left(S_{mn} \frac{\pi y}{d} \right) \cos \omega t.$$

With the help of the expansion

$$\sinh \left(S_{mn} \frac{\pi y}{d} \right) = - \sum_p \frac{8 p \cos p\pi}{\pi \left(4p^2 + S_{mn}^2 \frac{D^2}{d^2} \right)} \sinh S_{mn} \left(\frac{\pi D}{2d} \right) \sin \frac{2p\pi y}{D}$$

this formula can be rewritten as

$$E_{tr} = \sum_{v=1}^{\infty} \varepsilon_v \sin 2\pi \frac{vy}{D} \cos \omega t$$

where

$$\begin{aligned} \varepsilon_v = & - \frac{64vV}{\pi^2 d} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{n} \sin m\pi \frac{x}{d} \cos n\pi \frac{z}{L} \frac{\cos v\pi}{4v^2 + S_{mn}^2 \frac{D^2}{d^2}} u_x \\ & - \frac{64vV}{\pi^2 L} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{m} \cos m\pi \frac{x}{d} \sin n\pi \frac{z}{L} \frac{\cos v\pi}{4v^2 + S_{mn}^2 \frac{D^2}{d^2}} u_y. \end{aligned} \quad (11)$$

Let us now change variables, and write

$$Y = v(t - t_0) = y + \frac{1}{2}D \quad \text{with} \quad t_0 = -m\varphi_0/\omega. \quad (12)$$

With this notation, and a radio frequency $\omega = m(v/D) 2\pi$ equal to the m^{th} harmonic, the lateral electric force becomes

$$q \sum \varepsilon_v \sin v \frac{2\pi y}{D} \cos \omega t = q \sum \varepsilon_v \sin \left[\frac{v}{m} \omega t + v\varphi_0 - v\pi \right] \cos \omega t.$$

Here again the force has components of frequency $\omega \{ (v/m) \pm 1 \}$. It can indeed be put in the form

$$\frac{1}{2} q \sum E_v \sin \left[v\varphi_0 + \left(\frac{v}{m} + 1 \right) \omega t \right] + \frac{1}{2} q \sum E_v \sin \left[v\varphi_0 + \left(\frac{v}{m} - 1 \right) \omega t \right] \quad (13)$$

the $E_v = e_v \cos v\pi$. The comparison between lateral electric forces in circular and linear accelerators greatly reduces to a comparison between the two E_v appearing in (10) and (13). Differences should result from curvature effects. Figs. 7 to 10 show some data on the radial component of E_v . The differences between the curves for the circular and linear accelerators are quite noticeable for square cross-sections and strong

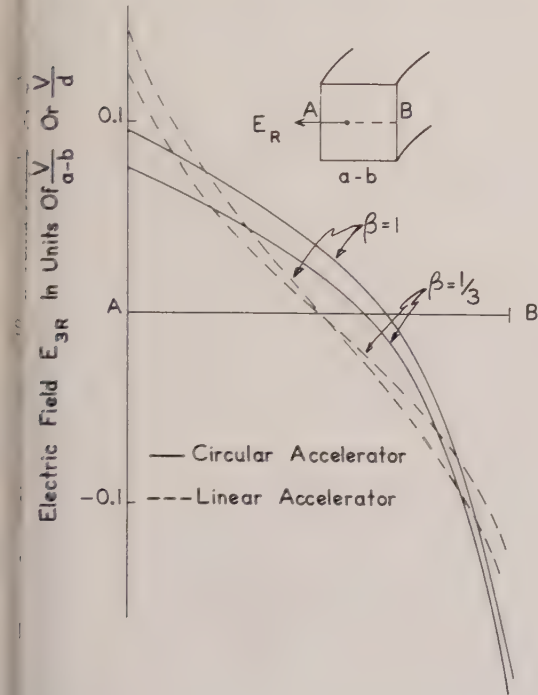


Fig. 7. Radial component of E_3 in the equatorial plane (i.e. along line AB) for a square cross-section and $\rho = \frac{2}{3}$.

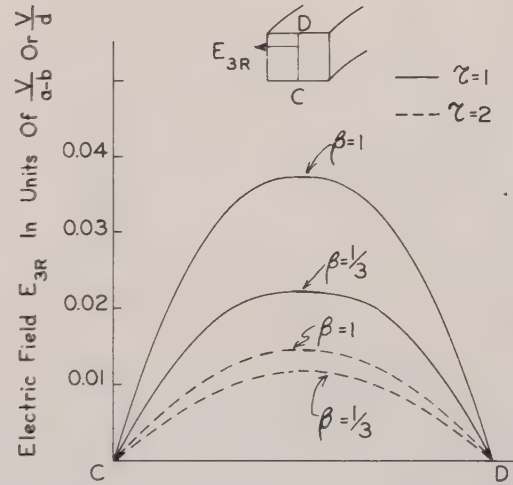


Fig. 8. Radial component of E_3 along a perpendicular CD to the equatorial plane at the center. Relative curvature $\rho = \frac{2}{3}$. For $\rho = \frac{1}{6}$, $\tau = 1$ this component is less than 10^{-3} .

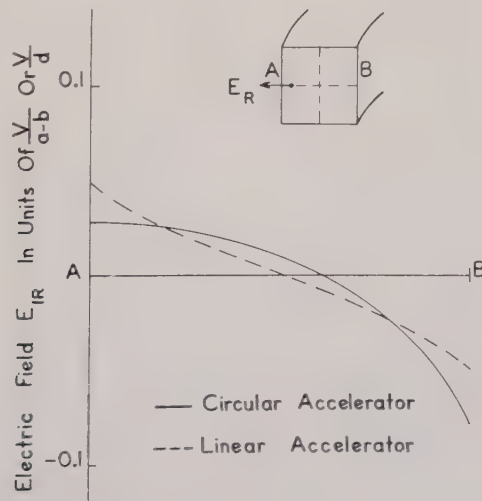


Fig. 9. Radial component of E_1 in the equatorial plane (i.e. along line AB) for a square cross-section and $\rho = \frac{2}{3}$, $\beta = 1$. The curves for $\beta = \frac{1}{3}$ are very close to those for $\beta = 1$, and are not shown explicitly.

curvatures, but have become almost negligible by the time the curvature has decreased to $\rho = \frac{1}{6}$, as can be inferred by looking at the field in the equatorial plane. The radial electric field along a perpendicular to that plane at the center of the cross section is zero for the linear accelerator. It does *not* vanish for the circular configuration, and its magnitude, compared to the magnitude along the equatorial plane, gives

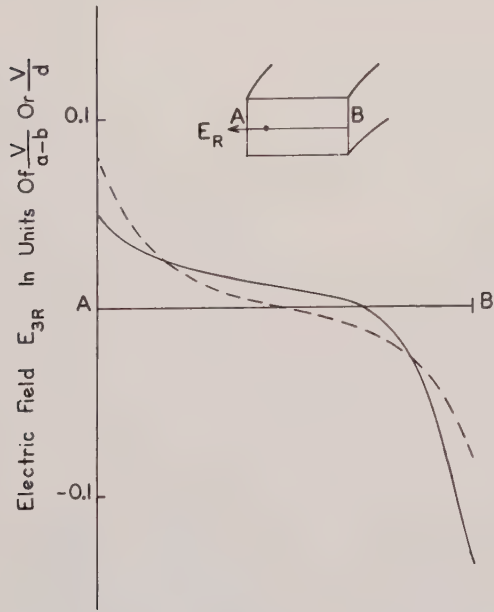


Fig. 10a

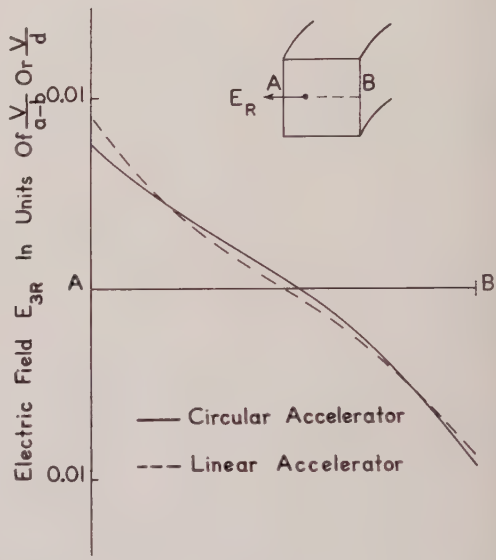


Fig. 10b

Fig. 10. Radial component of E_3 in the equatorial plane (i.e. along line AB) a. for $\beta = \frac{1}{3}$, $\rho = \frac{2}{3}$, and a rectangular cross section with $\tau = 2$ (curves for $\beta = 1$ are undistinguishable) b. for $\beta = \frac{1}{3}$, a square cross-section and weak curvature ($\rho = \frac{1}{6}$)

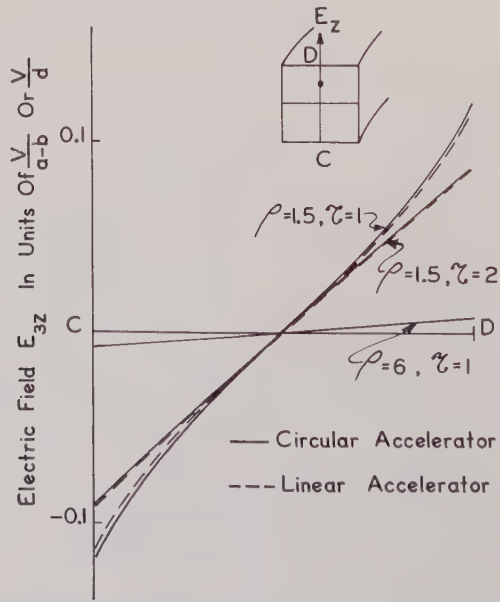


Fig. 11. Vertical component of E_3 along a perpendicular CD to the equatorial plane for $\beta = \frac{1}{3}$. For $\rho = \frac{1}{6}$ and $\tau = 1$, the two curves are undistinguishable.

mer estimate of the curvature effect. Some data on the z component of the electric field, which varies along the equatorial plane, are presented in fig. 11. Notice that the curvature has less influence on the vertical fields than on the horizontal fields.

Lateral Magnetic Forces

The meridian components of the magnetic field in the circular accelerator add up, from eq. (6), to a vector of the form

$$\sum H_v \cos v\varphi \sin \omega t.$$

A particle travelling on a circle, and with azimuth given by $\varphi = \varphi_0 + (\omega/m)t$ (i.e. with a linear velocity v), will be subjected to a lateral magnetic force

$$\frac{1}{2}qv\mu_0 \sum (u_\varphi \times H_v) \sin \left[v\varphi_0 + \left(\frac{v}{m} + 1 \right) \omega t \right] - \frac{1}{2}qv\mu_0 \sum (u_\varphi \times H_v) \sin \left[v\varphi_0 + \left(\frac{v}{m} - 1 \right) \omega t \right]. \quad (14)$$

It is desirable, in order to calculate this force, to have plots of H_v or, more conveniently, of $v\mu_0 u_\varphi \times H_v$ or $v\mu_0 H_{vr} u_z + v\mu_0 H_{vz} u_r$. In a similar manner, the transverse magnetic field in the straight tube is of the form

$$\sum_m \sum_n g_{mn}(x, z) \cosh \left(S_{mn} \frac{\pi y}{d} \right) \sin \omega t.$$

Using the expansion

$$\cosh \left(S_{mn} \frac{\pi y}{d} \right) = \sum_{p=0}^{\infty} \frac{4 \cos p\pi D}{\varepsilon_p \pi d} \frac{S_{mn}}{4p^2 + S_{mn}^2 \frac{D^2}{d^2}} \sinh \left(S_{mn} \frac{\pi D}{2d} \right) \cos p \frac{2\pi y}{D}.$$

where $\varepsilon_p = 1$ for $p = 0$, $\varepsilon_p = 2$ for $p = 1, 2, \dots$, we obtain the magnetic field in the form

$$\sum_{v=0}^{\infty} h_v \cos 2\pi \frac{vy}{D} \sin \omega t$$

or

$$\begin{aligned} & - \frac{32\varepsilon_0 V \omega D}{\pi^2 L} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{m} \cos m\pi \frac{x}{d} \sin n\pi \frac{z}{L} \frac{\cos v\pi}{\varepsilon_v \left[4v^2 + S_{mn}^2 \frac{D^2}{d^2} \right]} u_x \\ & + \frac{32\varepsilon_0 V \omega}{\pi^2} \sum_{1,3} \sum_{1,3} \frac{(-1)^{\frac{1}{2}(m+n)}}{n} \sin m\pi \frac{x}{d} \cos n\pi \frac{z}{L} \frac{\cos v\pi}{\varepsilon_v \left[4v^2 + S_{mn}^2 \frac{D^2}{d^2} \right]} u_z. \end{aligned} \quad (15)$$

For a particle whose motion is governed by equation (12), the magnetic force is given by

$$\frac{1}{2}qv\mu_0 \sum (u_y \times H_v) \sin \left[v\varphi_0 + \left(\frac{v}{m} + 1 \right) \omega t \right] - \frac{1}{2}qv\mu_0 \sum (u_y \times H_v) \sin \left[v\varphi_0 + \left(\frac{v}{m} - 1 \right) \omega t \right].$$

where $H_v = h_v / \cos v\pi$. It is desirable, to calculate this force, to have plots of

$$v\mu_0 (u_y \times H_v) = -v\mu_0 H_{vx} u_z + v\mu_0 H_{vz} u_x.$$

Figs. 12 to 14 display these components for a few typical parameters. They afford a comparison with the corresponding values for the circular accelerator. We shall call the vector $v\mu_0(u_y \times u_v)$, which has the dimension volt/meter, the "equivalent electric field" E_v^m . Figs. 12 and 13 display the horizontal component

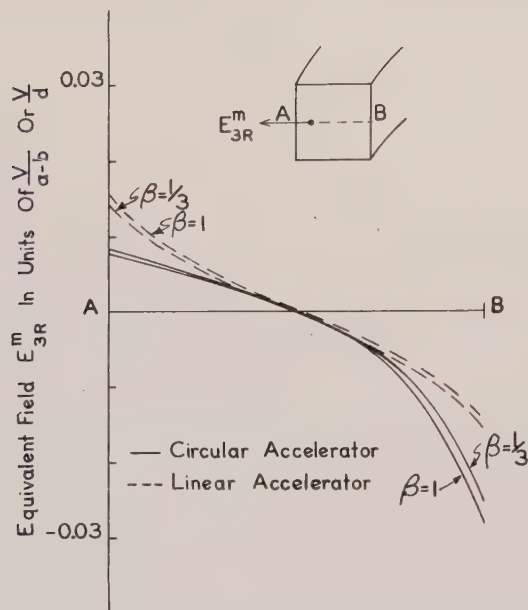


Fig. 12. Radial component of E_{3R}^m along the horizontal axis for a square cross-section, a curvature $\rho = \frac{2}{3}$, and two values of the velocity.

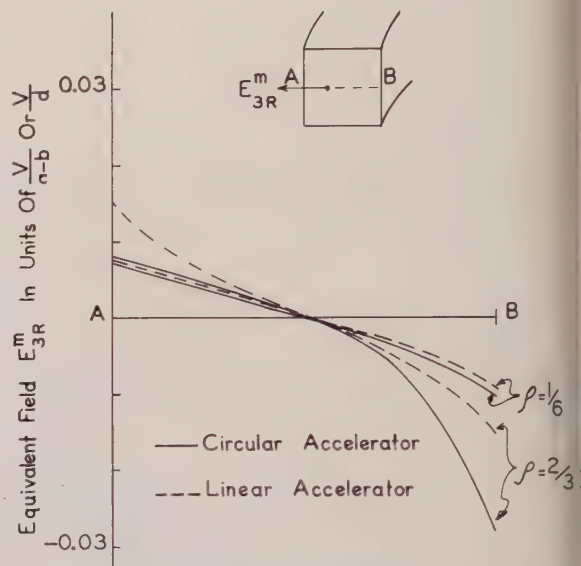


Fig. 13. Radial component of E_{3R}^m along the horizontal axis for a square cross-section, the velocity of light and two different curvatures.

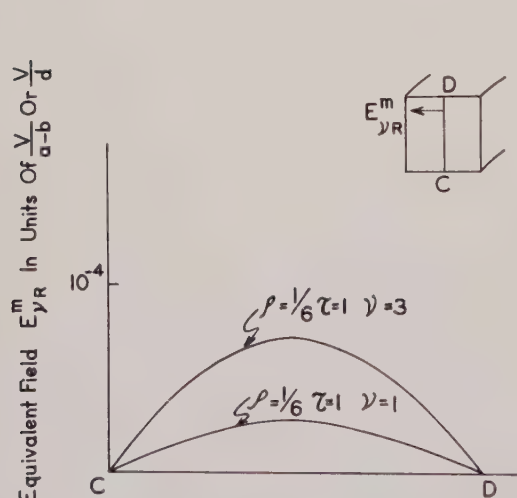


Fig. 14a

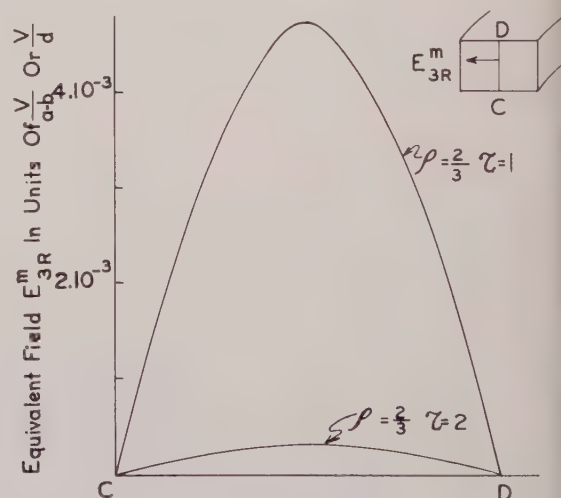


Fig. 14b

Fig. 14. Radial component of E^m along vertical axis through center for $\beta = 1$ and a variety of conditions.

of this field along the *horizontal* axis, and show the importance of curvature effects. This component vanishes along a *vertical* axis through the center for the linear accelerator, but not for the circular accelerator. The values shown in fig. 14 will consequently provide another measure of the influence of curvature.

The various graphs which have been displayed cover a rather restricted range of parameter values

will, however, allow a few qualitative conclusions which are quite valuable. Taking the most unfavorable cross-section, namely the square, and assuming a velocity of the order of the velocity of light, and that, for $\rho = \frac{2}{3}$ for example, the curvature effects are of the order of a few percent for $v = 1$, but become quite important for $v = 2$. For a relative curvature of $\rho = \frac{1}{6}$, we can go up to $v = 4$ before curvature effects become noticeable. Generalizing, we advance the opinion that, for the conditions mentioned above, curvature effects become noticeable for azimuthal numbers v of the order of the ratio $\frac{\text{radius } R}{\text{square } d}$, i.e. for fields having an azimuthal wavelength $2\pi R/v$ of the order of $2\pi d$ ($\lambda_\phi \approx d$). For other cross-sections the effects are reduced.

Acknowledgement

The various summations appearing in this report have been very ably programmed by Dr. J. McNall.

Appendix

The derivation of eqs. (5) and (6) can be outlined as follows. The accelerating structure of fig. 1 (also appearing in fig. 15) is really a flat coaxial line. The fields in a waveguide of any cross-section, excited through a hole in the cylindrical boundary surface, can be expressed as⁴⁾

$$E = A_0(z) \text{grad } \phi_0 + \sum_m \sum_p C_{mp}(z) \phi_{mp} u_z + \sum_m \sum_p A_{mp}(z) \text{grad } \phi_{mp} + \sum_m \sum_p B_{mp}(z) u_z \times \text{grad } \psi_{mp} \quad (16)$$

$$H = \alpha_0(z) u_z \times \text{grad } \phi_0 + \sum_m \sum_p \gamma_{mp}(z) \psi_{mp} u_z + \sum_m \sum_p \alpha_{mp}(z) u_z \times \text{grad } \phi_{mp} + \sum_m \sum_p \beta_{mp}(z) \text{grad } \psi_{mp} \quad (17)$$

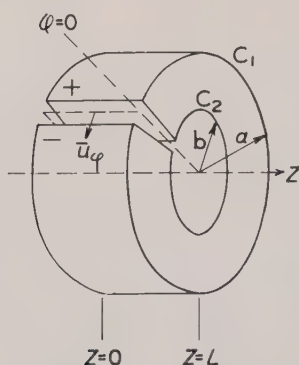


Fig. 15. Short coaxial line.

where the ϕ 's and the ψ 's are the eigenfunctions of the two-dimensional Laplacian in the cross-sectional plane, corresponding to Dirichlet and Neumann boundary conditions on the limiting contour (i.e. $\phi = 0$, $\psi_n = 0$ on c_1 and c_2). ϕ_0 , in particular, exists in doubly (or multiply) bounded cross-sections only, and is the electrostatic potential obtained by applying a constant potential difference between the two boundary curves. For a coaxial line, the eigenfunctions are,

$$\phi_0 = \ln r$$

$$\phi_{mp} = R_m(\mu_{mp} r) \begin{cases} \sin m\phi \\ \cos m\phi \end{cases}$$

$$\psi_{mp} = S_m(\nu_{mp} r) \begin{cases} \sin m\phi \\ \cos m\phi \end{cases}$$

where the R_m and S_m have been defined in (3) and (4). The still unknown z -dependent coefficients can be found from the following differential equations, taken from ref.⁴),

$$\begin{aligned}\frac{dA_0}{dz} + j\omega\mu\alpha_0 &= \frac{d\alpha_0}{dz} + j\omega\epsilon a_0 = 0 \\ \frac{dA_{mp}}{dz} + j\omega\mu\alpha_{mp} - C_{mp} &= \frac{d\alpha_{mp}}{dz} + j\omega\epsilon A_{mp} = \alpha_{mp} + \frac{j\omega\epsilon}{\mu_{mp}^2} C_{mp} = 0 \\ \frac{d\beta_{mp}}{dz} - j\omega\epsilon B_{mp} - \gamma_{mp} &= \frac{dB_{mp}}{dz} - j\omega\mu\beta_{mp} = 0 \\ B_{mp} - \frac{j\omega\mu\gamma_{mp}}{v_{mp}^2} &= \frac{V}{v_{mp}^2 \iint \psi_{mp}^2 r dr} \begin{Bmatrix} 0 \\ S_m(v_{mp}a) - S_m(v_{mp}b) \end{Bmatrix}\end{aligned}$$

and where we have made use of the fact that $E_z = 0$ and $E_\phi = (V/a) \delta(\phi)$ at $r = a$, $E_\phi = (V/b) \delta(\phi)$ at $r = b$ along the cylindrical boundary. To solve these differential equations, we still need boundary conditions at $z = 0$ and $z = L$. For these values of z , the tangential electric field is imposed: it is $(V/r)\delta(\phi) u_\phi$. If we set $z = 0$ and $z = L$ in (16), and equate the transverse part of the right hand side (i.e. all terms but those of the form $c\phi u_z$) to $(V/r)\delta(\phi) u_\phi$, we find

$$\begin{aligned}A_0 &= 0 \\ A_{mp}(0) = A_{mp}(L) &= \frac{mV}{\mu_{mp}^2 \iint \phi_{mp}^2 r dr} \begin{Bmatrix} \int_b^a \frac{R_m}{r} dr \\ 0 \end{Bmatrix} \\ B_{mp}(0) = B_{mp}(L) &= \frac{V}{v_{mp}^2 \iint \psi_{mp}^2 r dr} \begin{Bmatrix} 0 \\ S_m(v_{mp}a) - S_m(v_{mp}b) \end{Bmatrix}.\end{aligned}$$

These relations allow the determination of all z dependent coefficients in (16) and (17), and lead, after a few trivial analytical steps, to eqs. (5) and (6) of the text.

CALCULATION OF THE PULSE-HEIGHT RESPONSE OF NaI(Tl) SCINTILLATION COUNTERS

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Monte Carlo calculation to determine the pulse-height response of NaI(Tl) scintillation counters to gamma rays is described. Comparisons of several calculations with experiments using 3-in.-dia by 3-in.-high crystals for source energies from 0.32 to 7.48 MeV are presented and show good agreement for large pulse heights. At small pulse heights the calculations underestimate the experimental data and indicate that

background radiation can contribute significantly to the experimental results. An extensive series of calculations are reported for a 3-in.-dia by 3-in.-high crystal using monoenergetic, point isotropic sources placed on the crystal axis 10 cm from one end. The source energy ranged from 0.1 to 6.0 MeV in this series of calculations.

Introduction

With the increased use of NaI(Tl) scintillation counters for gamma-ray spectroscopy much time has been devoted to producing pulse-height response spectra from monoenergetic sources for reference¹⁾ for use in unfolding complex spectra. Although considerable experimental data are now available, theoretical calculations have become an increasingly important method for supplementing experimental data in energy regions where monoenergetic sources are not available.

Several Monte Carlo calculations have been reported for crystals of various sizes and source energies. In general, these calculations have not been comprehensive for any particular crystal size and have been additionally restricted to low source energies where secondary energy losses by bremsstrahlung and annihilation radiation are unimportant^{2,3)}. The recent work of Miller and Snow⁴⁾ is an exception to the energy restriction. In their calculations they were able to extend the source energy to 8 MeV by taking secondary losses into account.

The purpose of this paper is to present the results of an extensive series of Monte Carlo calculations for a 3-in.-dia by 3-in.-high NaI(Tl) counter with an isotropic point source of monoenergetic gamma rays on the crystal axis 10 cm from one

end. In this study energy losses by secondary radiation were included and the calculations were performed for source energies from 0.1 to 6.0 MeV.

The major difference between this calculation and previous ones is that a statistical estimation and a weighting procedure were employed rather than analogue Monte Carlo techniques. The principle advantage of this procedure over analogue Monte Carlo techniques is that of reducing the variance of the estimates for a given sample size, or, alternatively, of reducing the sample size for the same variance.

In Sections 2 and 3, a general description is given of the Monte Carlo calculation that was programmed for computation on the IBM-704 automatic computing machine. A description of the code and its applicability to several alternate source-counter configurations has been presented elsewhere⁵⁾. Comparisons of some typical calculations with experimental pulse-height response spectra from NaI(Tl) crystals are presented in Section 4. The results of calculations for a 3-in.-dia by 3-in.-high NaI(Tl) crystal are presented in Section 5.

¹⁾ R. L. Heath, AEC Research and Development Report IDO-16408 (1957).

²⁾ M. J. Berger and J. Doggett, J. Research Natl. Bur. Standards **56** (1956) 355.

³⁾ C. M. Davisson and L. A. Beach, U.S. Naval Research Laboratory Report NRL-5408 (1959).

⁴⁾ W. F. Miller and W. J. Snow, Rev. Sci. Instr. **31** (1960) 39.

⁵⁾ C. D. Zerby and H. S. Moran, Oak Ridge National Laboratory Report CF-60-5-72 (1960).

† Operated by Union Carbide Corporation for the U.S. Atomic Energy Commission.

2. Idealizations and Assumptions

The basic idealization of the source-counter configuration in the Monte Carlo calculation was that of suspending it in a vacuum. Background effects, which in any case are unique for a particular experimental arrangement, are thus completely eliminated. The difference between calculation and experiment produced by this idealization is expected to be significant in the region of low pulse height and in the region of low response such as in the valley between the total absorption peak and the energy loss spectra for low energy sources.

The response of the crystal was assumed to be proportional to the energy deposited. This is actually not the case for a real crystal which has been shown to have a linear but not proportional response for totally absorbed photons above 70 keV⁶). In fact, it is just this effect which has been shown to cause an additional source of line broadening⁷). However, since the calculations are first carried out as if the crystal produced a sharp line in response to the energy deposition and the response spectrum was subsequently spread out by a Gaussian broadening which includes all contributions (see Section 3.5), the assumption of proportionality should produce little error in the shape of the curves.

In the transport of the photons through the crystal it was assumed that only photoelectric events, pair production, and Compton scattering could take place. The total cross section for the latter process was determined from the Klein-Nishina formula and the others obtained from the tabulated values given by Grodstein⁸). Since the photoelectric cross section increases rapidly as the photon energy decreases, photons degraded below 5.11 keV were assumed to be totally absorbed. For Compton events, which are the main source of energy degradation for the photons, the angle and energy of the scattered photons were selected from the differential Klein-Nishina formula for unpolarized primary radiation.

The obvious neglect of Rayleigh scattering in the transport of photons actually amounts to the

approximation that the photons scattered by the process are directed straight ahead without energy degradation. The lack of energy degradation is very accurate in this case because of the small energy transmitted to the recoiling atom, and the straight ahead approximation, which increases in accuracy as the photon energy increases, is sufficiently valid in the energy range considered in this problem so that errors in the response spectra should be within the statistical accuracy of the calculation.

The charged particles ejected by photon processes play an important part in the determination of the response spectra since they lead to energy loss from the crystal through the secondary radiation they produce. The initial energy of these charged particles, the important parameter for determining the source strength of the bremsstrahlung radiation, was obtained in the following way: for Compton events the electron energy was determined from the kinematics of the collision; for photoelectric events the kinetic energy of the electron was set equal to the energy of the incident photon; and for pair production the excess kinetic energy was distributed between the electron and positron according to the Born approximation by a random selection technique. All these charged particles were assumed to slow down and stop at their point of origin. This can be justified on the basis that the residual path length of a typical particle is small compared with the dimensions of the crystal for energies considered here† and the actual distance from the origin to the stopping point is smaller because of the deviant path taken.

The spectrum of the bremsstrahlung radiation emitted by the charged particles shown in fig. 1 was taken from a previous calculation which used a continuous slowing-down model and the bremsstrahlung cross section given by the Born approximation⁹). The direction of emission of the bremsstrahlung radiation was selected from a

⁶) D. Engelkemeir, *Rev. Sci. Instr.* **27** (1956) 589.

⁷) C. D. Zerby, A. Meyer and R. B. Murray, *Nucl. Instr. and Meth.*, **12** (1961) 115.

⁸) G. W. Grodstein, *Natl. Bur. Standards Report NBS-50* (1957).

⁹) C. D. Zerby and H. S. Moran, *Oak Ridge National Laboratory Report, ORNL-2454* (1958).

† Electrons with energies of 1.0, 4.0 and 6.0 MeV have residual path lengths of 0.2, 0.9 and 1.3 cm, respectively, in NaI(Tl).

isotropic distribution. This was done because electrons at energies considered here diffuse in almost random direction after they have lost only a small amount of energy; hence, most of the brems-

as can be seen in fig. 1; therefore the assumption of isotropy for all bremsstrahlung radiation should not introduce a serious error.

For the annihilation radiation it was assumed that the positron came to rest before the emission of two photons having one electron rest mass energy each. Actually this is a good approximation at the energies considered here since over 90% of the positrons will be stopped before annihilation¹⁰. As a result of the approximation one of the annihilation photons was selected from an isotropic distribution and the other one given a direction directly opposite to the first to maintain conservation of momentum.

3. The Computational Procedure

3.1. CALCULATION OF THE INTRINSIC EFFICIENCY

The Monte Carlo calculation was started by determining the direction of incidence of the source radiation on the crystal by systematically sampling the isotropic point source within the cone subtended by the crystal. The probability of making at least one collision in the crystal was then calculated for each sample from the expression $1 - \exp(-\Sigma_0 x)$, where Σ_0 is the total cross section at the source energy and x is the total path length through the crystal for the particular sample. These quantities were then averaged to yield the intrinsic efficiency.

This procedure actually amounts to a numerical integration because the source was systematically sampled and yields a value of the intrinsic efficiency which has an error of less than 0.1% in most cases.

3.2. CALCULATION OF THE ANALYTIC ZERO INTERCEPT

The pulse-height response spectrum for each source energy was calculated in units of counts per unit energy (pulse height) for one particle incident on the crystal and then normalized for convenience in presentation. The intercept of the unnormalized spectrum with the zero pulse-height value can actually be calculated very accurately and is quite useful for terminating the curves through the statistical estimates of the spectrum. The method of calculating this end point value can be determined

¹⁰ W. Heitler, *The Quantum Theory of Radiation*, 3rd Ed., (Oxford University Press, London, 1954) p. 385.

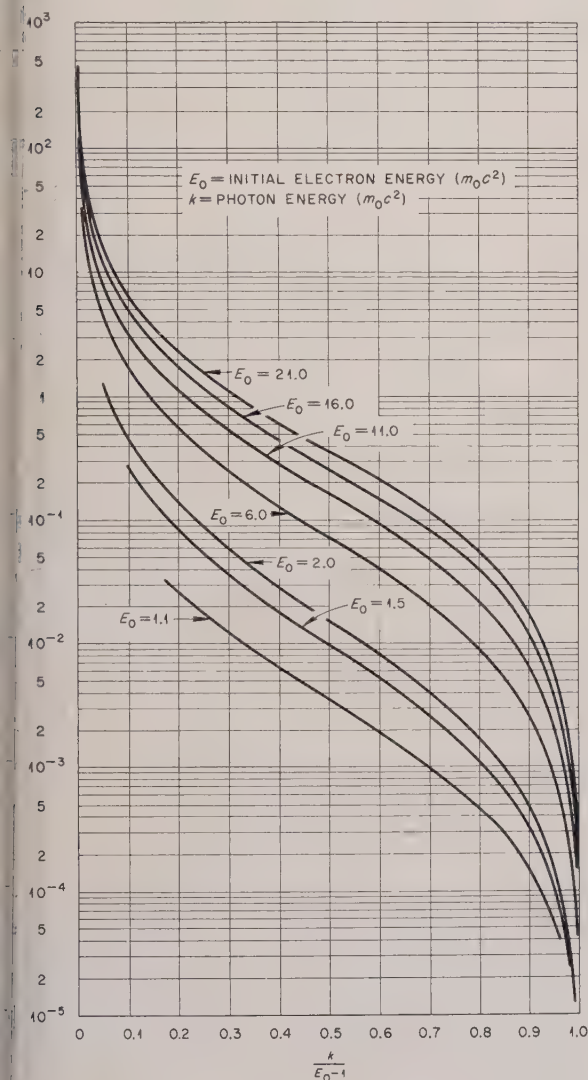


Fig. 1. Bremsstrahlung spectra from an electron slowing down in an infinite sodium iodide crystal. The curves are labeled with the initial total energy (kinetic plus rest mass energy) of the electron in rest mass units.

strahlung photons will be emitted isotropically. Only the direction of the highest energy bremsstrahlung photons will be correlated with the initial direction of the electron since they must be emitted before the electron has lost much energy by reflecting collisions. However, the probability of emitting the high energy photons is relatively small

easily if one notes that photons which scatter straight ahead only once before escaping are the only ones that contribute in the limit of zero pulse height. Thus it can be shown that the average value of the quantities obtained from the expression $(d\Sigma/dE)_0 x \exp(-\Sigma_0 x)$ for each source sample is the desired quantity. The expression $(d\Sigma/dE)_0 = 2\pi r_0^2 N m_0 c^2 / E_0^2$, where N is the electron density, r_0 is the classical electron radius, and E_0 is the source energy, was obtained from the differential Klein-Nishina formula in the limit of straight-ahead scattering. The quantities Σ_0 and x are the same as defined above.

This calculation again amounts to a numerical integration because the source was systematically sampled.

3.3. DETAILS OF THE CASCADE AND CALCULATION OF THE RESPONSE SPECTRUM

Once a source photon was permitted to enter the crystal it was never allowed to escape or to be absorbed. To adjust for this unnatural behavior a weight was carried along with each sample photon which represented its survival probability. At every collision point the primary photon was only allowed to scatter and the weight, which was initially set to unity, had to be multiplied by a factor equal to the probability of scattering (the ratio of scattering to total cross section). After the scattering collision the distance, y , to the exit surface of the crystal was first calculated and then the randomly selected distance to the next collision was obtained from a truncated exponential distribution so that the distance was always less than or equal to y . In this case the weight of sample had to be multiplied by the factor $1 - \exp(-\Sigma y)$, where Σ is the total cross section at the current energy of the photon, in order to account for the fact that its escape was not allowed.

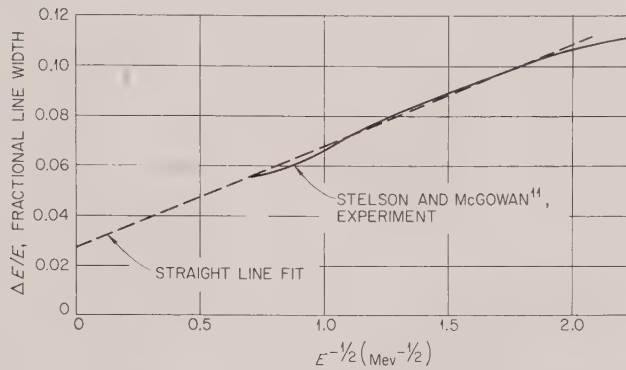
The principle use of the weights is described below; however, it is appropriate to note here that when the weight decreased below the value 0.001 the history was terminated and the current energy taken to be totally absorbed. This is another way of terminating the history other than when the energy was degraded below 5.11 keV as noted above.

After each scattering collision of the primary

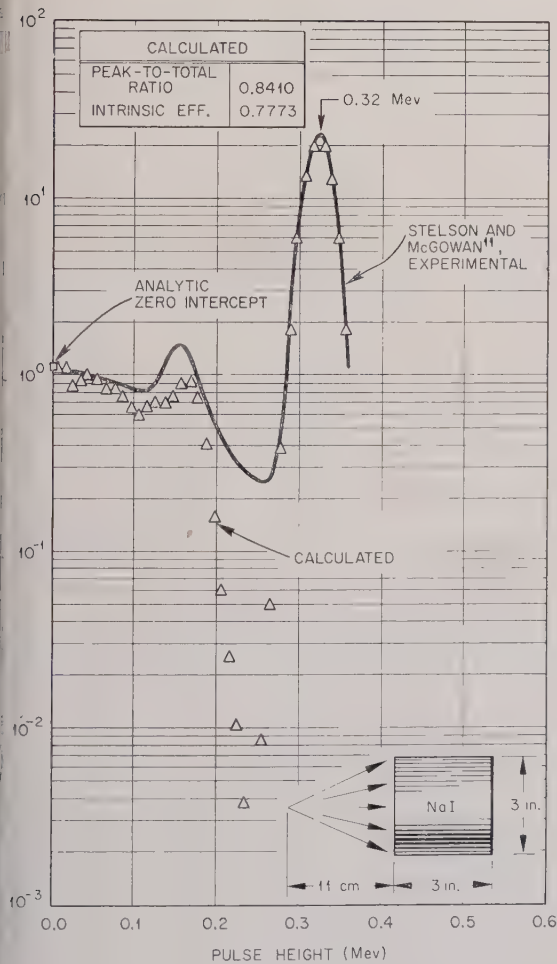
radiation the energy of the ejected electron was determined so that the energies of the bremsstrahlung photons emitted in the slowing-down process could be obtained by a systematic sampling procedure from the data presented in fig. 1. Each of these photons and all cascade radiation derived from them such as bremsstrahlung and annihilation radiation were followed by an analogue Monte Carlo method to obtain the total energy lost from the crystal. This information was then used in the calculation of the response spectrum.

With the procedure as described above it was possible to calculate a contribution to the response spectrum after each scattering collision of the primary radiation. This was done by taking the current weight of the photon and multiplying by the probability of escape, $\exp(-\Sigma y)$, and adding the product into the pulse-height interval which included the total energy deposited up to that particular collision. In this case the energy deposited is the source energy minus the current energy of the photon minus all energy lost from the crystal by secondary radiation originating from all previous Compton events.

The additional contributions required to determine completely the response spectrum were obtained by first treating each collision of the primary radiation as a photoelectric event and then as a pair production event (if the energy was above threshold) before actually allowing the photons to scatter. In the case of a photoelectric event the energy lost from the crystal by all secondary radiation produced by the photoelectron was calculated in the same way as for a Compton ejected electron. The weight of the primary photon before the collision was then multiplied by the probability of having a photoelectric event and the product was added into the pulse-height interval corresponding to the energy deposited. The energy deposited in this case is the source energy minus the energy lost from the crystal by all secondary radiation initiated by the photoelectron minus the energy lost from the crystal by secondary radiation from all previous Compton events. The contribution from pair production was calculated in a similar manner; however, the loss of the secondary annihilation radiation also had to be accounted for.



2. Fractional line width, $\Delta E/E$, for a 3-in.-dia by 3-in.-high NaI(Tl) crystal as a function of $E^{-1/2}$. Here E is the energy absorbed by the crystal in units of MeV and ΔE is the line width at half maximum.



3. Calculated and experimental response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 0.32-MeV incident gamma rays. The isotropic point source was located 11 cm from the end of the crystal.

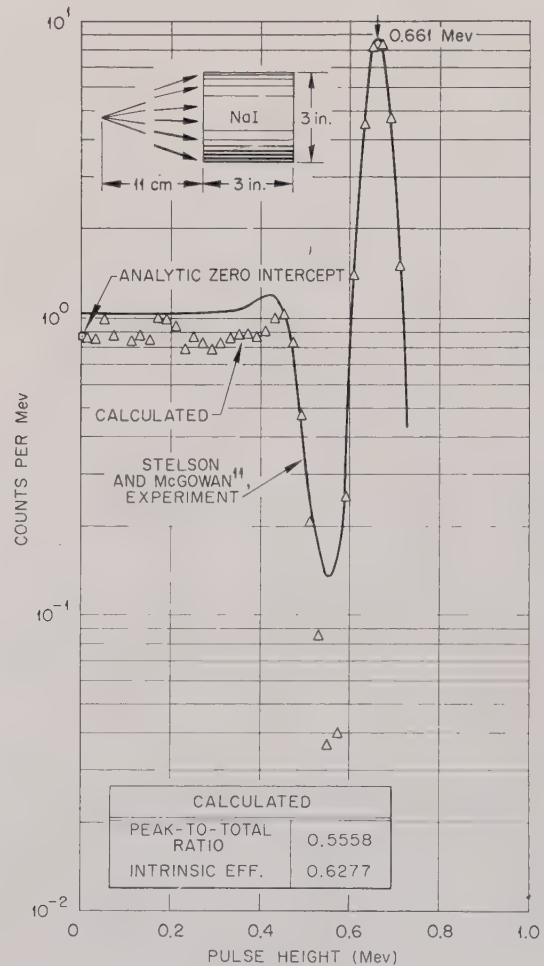


Fig. 4. Calculated and experimental response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 0.661-MeV incident gamma rays. The isotropic point source was located 11 cm from the end of the crystal.

3.4. CALCULATION OF THE PEAK-TO-TOTAL RATIO

For purposes of computing the peak-to-total ratio, all counts for which the energy deposition was within 5.11 keV of the source energy were treated as occurring in the total absorption peak. The ratio of these counts to all counts was then taken as the peak-to-total ratio.

It should be noted that a slightly different value of the ratio would be obtained at the higher source energies if the spectrum was broadened first and then the total absorption peak peeled off from the overlapping energy-loss spectrum. This occurs because the buildup of counts near the total absorption peak caused by small bremsstrahlung losses are not easily separable from the peak and are usually included in it.

3.5. BROADENING OF THE SPECTRUM

From the discussion of the calculation of the response spectrum, it should be noted that no account was taken of the line broadening when the spectrum was initially determined. This was compensated for in an auxiliary calculation which produced the broadened spectrum, $g(E)$, from the unbroadened spectrum, $k(E)$, by performing the integral

$$g(E) = \int_0^{E_0} k(E')F(E, E') dE'$$

where $F(E, E') = (\pi\sigma^2)^{-\frac{1}{2}} \exp[-\frac{1}{2}(E - E')^2\sigma^{-2}]$. Here the term σ is related to the line width at half maximum, ΔE , by the relation $\Delta E = (8 \log_e 2)^{\frac{1}{2}}\sigma$.

A convenient expression for σ turns out to be

$$\sigma = A\sqrt{E} + BE \quad (1)$$

as can be seen in fig. 2 where the experimental fractional line width, $\Delta E/E$, is given as a function of $E^{-\frac{1}{2}}$ in which case it can easily be fit by a straight line. The solid curve in fig. 2 is a smooth fit to the unpublished experimental data obtained at the Oak Ridge National Laboratory for a 3-in.-dia by 3-in.-high NaI(Tl) crystal¹¹). In this case the straight line data yields values of the constants A and B of $0.01703 \text{ (MeV)}^{\frac{1}{2}}$ and 0.01147 , respectively.

4. Comparison with Experiment

Shown in figs. 3 through 7 are comparisons of the calculation with various experimental results for 3-in.-dia by 3-in.-high NaI(Tl) crystals for source

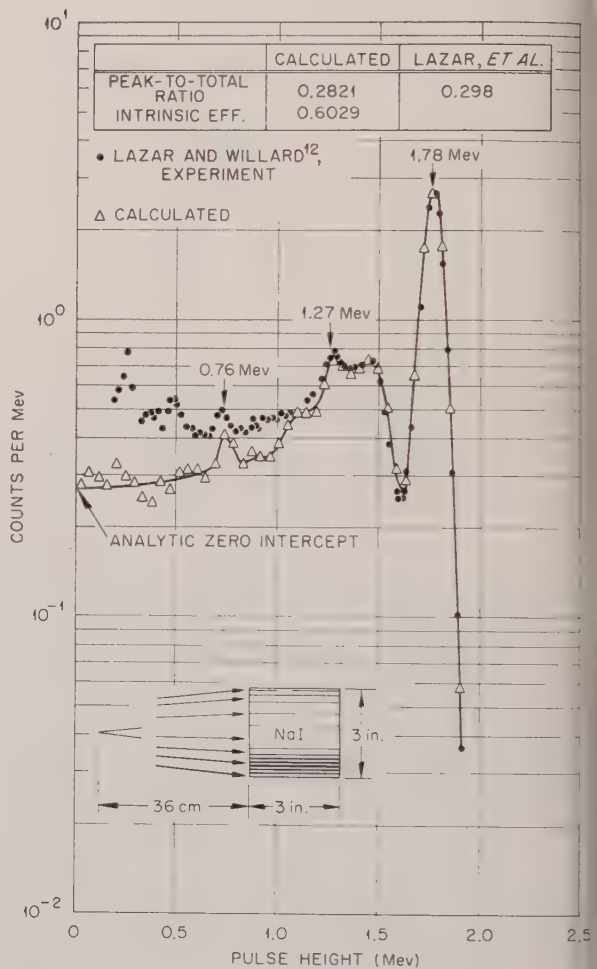


Fig. 5. Calculated and experimental response spectrum from 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 1.78 MeV incident gamma rays. The isotropic point source was located 36 cm from the end of the crystal.

energies from 0.32 to 7.48 MeV. In all these figures the pulse height is given in units of MeV and the calculated data are normalized to a total response of one count. For comparison the experimental data were normalized to the calculated data at the total absorption peak. The constants used in eq. (1) for broadening the spectrum were chosen to best fit the experimental data in each case. Each calculation is

¹¹) Unpublished data of P. H. Stelson and F. K. McGowan, Oak Ridge National Laboratory.

a result of 2000 samples from the source. Figures 3 and 4 show the experimental results of Larson and McGowan¹¹). In their experiments the meter was suspended in the middle of a room by a

For source energies above 1 MeV the calculated data were compared with the experimental data of Lazar and Willard¹²) and are shown in figs. 5 through 7. In these comparisons the calculation

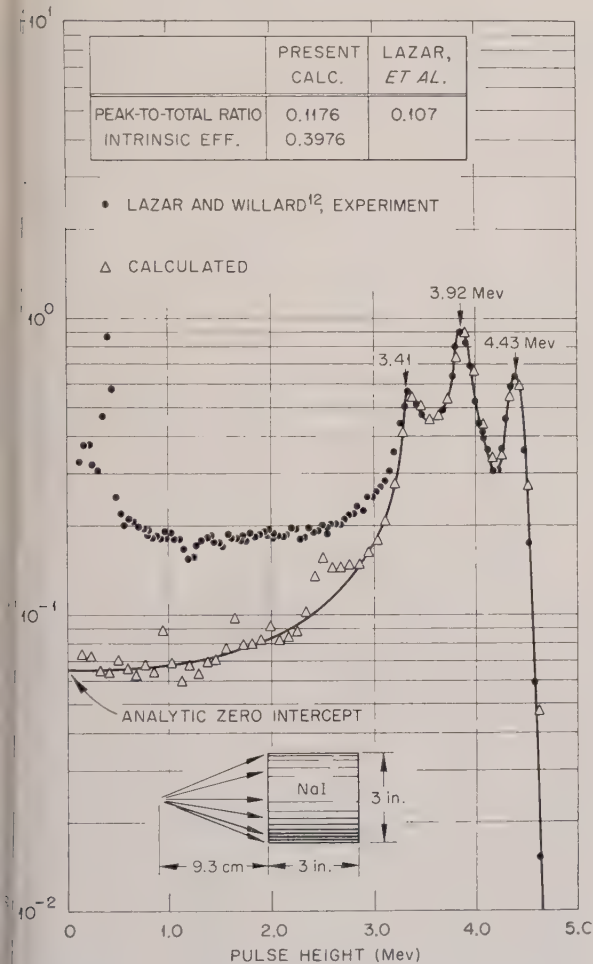


Fig. 6. Calculated and experimental response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 4.43-MeV incident gamma rays. The isotropic point source was located 9.3 cm from the end of the crystal.

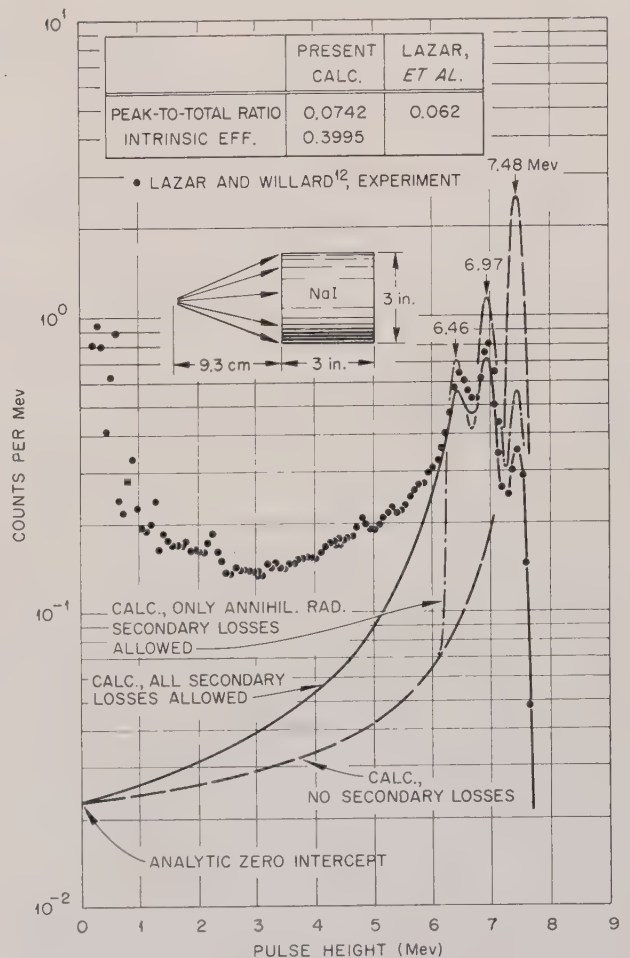


Fig. 7. Calculated and experimental response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 7.48-MeV incident gamma rays. The isotropic point source was located 9.3 cm from the end of the crystal.

minimum support in order to minimize background effects, and the resultant pulse-height spectrum is adjusted in an attempt to remove the remaining background contributions. The calculated data show a deeper valley just below the total absorption peak of the adjusted experimental data and tend to underestimate the same data at the smaller pulse heights. This deviation can be attributed to background effects that were not counted for in adjusting the experimental data.

again gives an underestimate of the experimental data at small pulse-height values although there is very good agreement at the larger pulse heights. The deviation between the calculated and experimental data in these cases must also be attributed to background contributions in the experiment rather than statistical underestimates of the calculation. This is based on the fact that the

¹²) N. H. Lazar and H. B. Willard, Oak Ridge National Laboratory Report, ORNL-2076 (1956) 55.

calculation is verified at both extremes of the pulse-height spectrum; at the large pulse heights the calculation agrees with experiment and at the small

experimental data. This does not necessarily indicate that the calculation is incorrect, because the difference could be accounted for by the ap

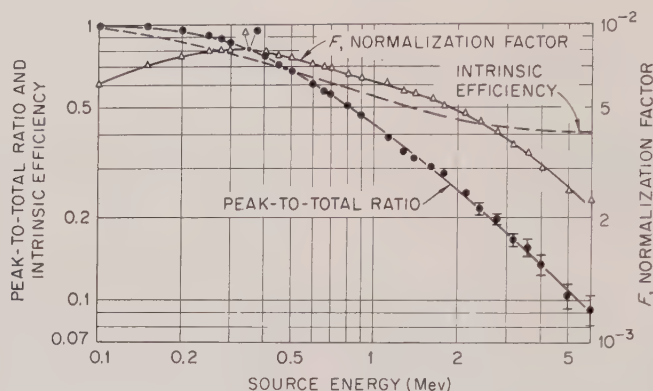


Fig. 8. Calculated values of the peak-to-total ratio, intrinsic efficiency, and the normalization factor, which is described in the text, as a function of source energy for a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter. The source was an isotropic point located 10 cm from the end of the crystal.

pulse heights the statistical data approaches the analytic zero intercept (see Section 3.2) with a fair degree of accuracy.

In the case of the 7.48-MeV source, shown in fig. 7, the calculated data are represented by a smooth curve in order to simplify the figure and show some additional data indicating the effect of secondary radiation on the pulse-height response spectrum. The curve labeled "no secondary losses" was calculated by letting all secondary radiation be absorbed. The curve labeled "only annihilation radiation secondary losses allowed" was calculated by letting the bremsstrahlung radiation be absorbed and tracing only the annihilation radiation. The last curve, which is labeled "all secondary losses allowed," took account of both annihilation and bremsstrahlung energy losses. As would be expected, the curve neglecting all secondary losses does not agree with experiment at all. The curve including annihilation radiation losses agrees with experiment fairly well when the experimental data are normalized to it at the total absorption peak; however, the relative heights of the two escape peaks do not agree with experiment until all secondary losses are included. It can be observed that for the case where all secondary losses are allowed the two escape peaks lie below the ex-

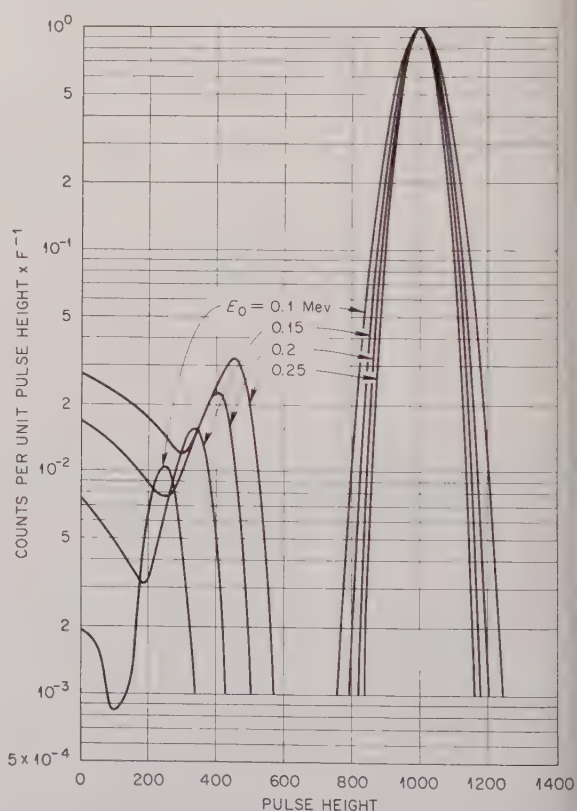


Fig. 9. Calculated response spectra from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for 0.1-, 0.15-, 0.2-, and 0.25-MeV monoenergetic sources. The source was an isotropic point located 10 cm from the end of the crystal.

ably large amount of background appearing in the experiment. If the calculated data were normalized to the experimental data at the first escape peak, for example, the calculated total ab-

standard deviations and was determined in the calculation. At energies below 1.3 MeV the error is not indicated because it falls within the circles marking the data points.

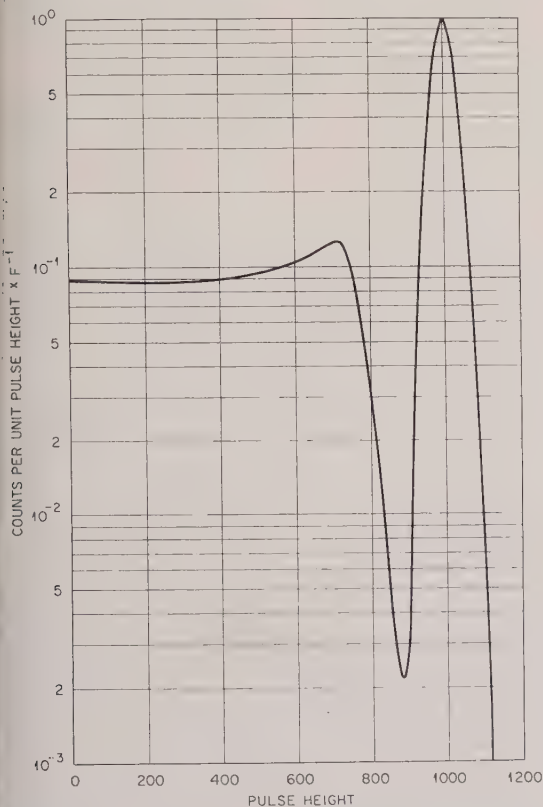


Fig. 10. Calculated response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for a 0.8-MeV source. The source was an isotropic point located 10 cm from the end of the crystal.

orption peak would be approximately 10% higher than the experimental value.

Results of the Calculation

A series of calculations for a 3-in.-dia by 3-in.-high NaI(Tl) crystal were performed with a monoenergetic point source on the crystal axis 10 cm from one end. The source energy ranged from 0.1 to 10 MeV for these cases, and for each source energy 1000 samples of the primary source radiation were traced along with all secondary radiation as discussed in Section 3.3. The intrinsic efficiency and peak-to-total ratios for these cases are presented in Fig. 8. The error interval indicated at the data points for the peak-to-total ratio spans two

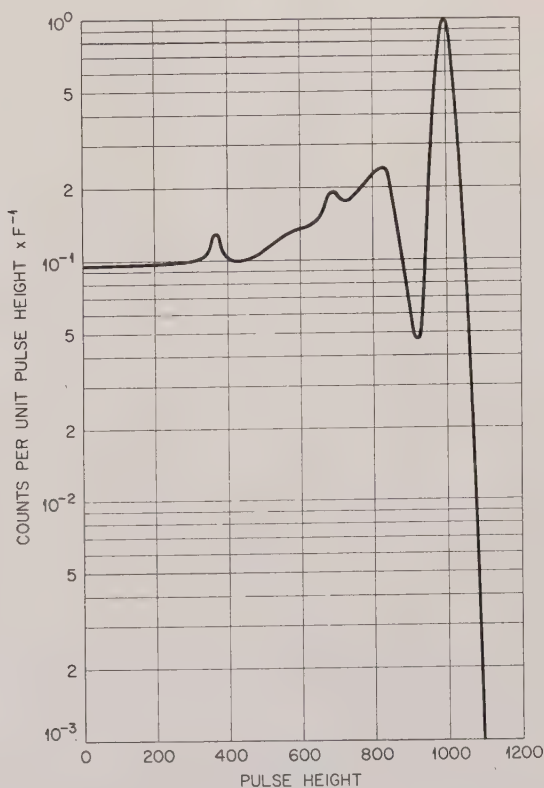


Fig. 11. Calculated response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for a 1.6-MeV source. The source was an isotropic point located 10 cm from the end of the crystal.

For comparison purposes the response spectra from a few of these cases are presented in Figs. 9 through 13. These spectra have been broadened using the constants A and B in eq. (1) that were derived from Fig. 2 (see Section 3.5). In all cases the curves were drawn so that the total absorption peak was located at a pulse height of 1000 and had a height of unity. By multiplying the ordinate of each of these graphs by the normalization factor F , which is given in Fig. 8 as a function of source energy, the response spectra will be normalized to a total response of one count.

The smooth curves shown in Figs. 9 through 13 were drawn on the assumption that the data

would be of most use if presented in this form. This does not imply that these data have greater accuracy than the calculated data presented in figs. 3 through 7. Figures 5 and 6, in fact, show typical

the photons escapes and the other escapes after one scattering. It is essentially the appearance of the Compton peak for annihilation radiation. It is prominent at 1.6 MeV because the escape peaks

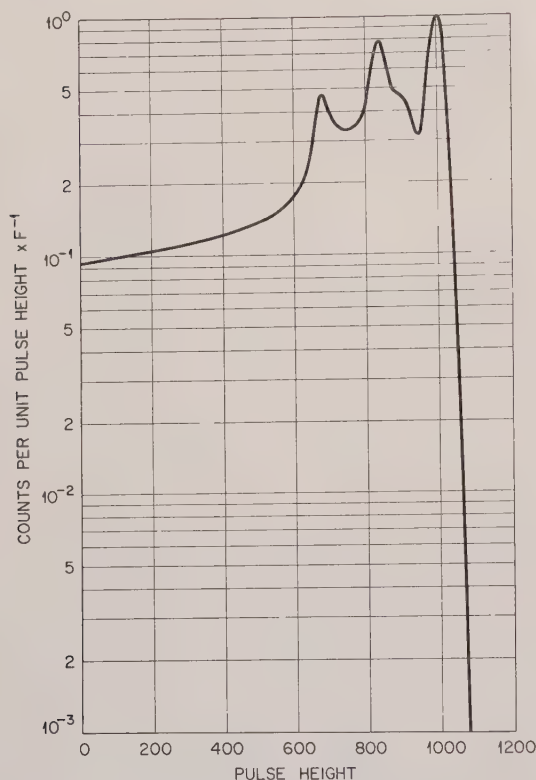


Fig. 12. Calculated response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for a 3.13-MeV source. The source was an isotropic point located 10 cm from the end of the crystal.

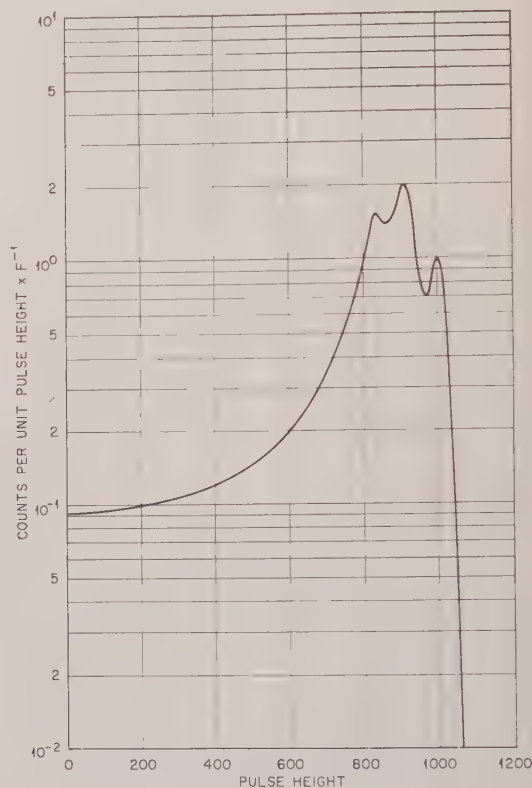


Fig. 13. Calculated response spectrum from a 3-in.-dia by 3-in.-high NaI(Tl) scintillation counter for a 6.0-MeV source. The source was an isotropic point located 10 cm from the end of the crystal.

examples of how the smooth curves were drawn through the statistical data. The over-all accuracy of the calculation can be observed by inspecting the errors indicated on the peak-to-total ratios shown in fig. 8.

The change in the spectrum as the source energy changes is obvious from figs. 9 through 13. One feature of the spectrum is worth a brief discussion, however, and that is the slight hump that appears between the two escape peaks for a 1.6-MeV source energy as seen in fig. 11. This hump is apparently caused by the annihilation radiation where one of

have not built up sufficiently to mask the hump when they are broadened. This effect can also be observed in fig. 5 which shows the response of a crystal to a 1.78-MeV source.

Acknowledgements

The authors are indebted to P. R. Bell who originally suggested this problem and to R. W. Peelle and G. T. Chapman for many helpful discussions. We wish to thank P. H. Stelson and F. K. McGowan for granting us the use of unpublished experimental data.

A NON-INTERCEPTING ACCELERATOR BEAM POSITION SENSOR†

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A non-intercepting beam position sensor consisting of two sets of pick-up coils, resonant tuned, are used with a differential amplifier and an oscilloscope to determine the spatial position of a pulsed beam from an electron linear accelerator. A pulsed beam of 100 mA peak can be positioned to about 0.5 mm.

Recent work indicates the feasibility of using this position sensor technique with an external cyclotron beam. The design, method of construction, and performance of the linac sensor is discussed. A brief summary of the cyclotron sensor is given.

Introduction

With the many advancements in experimental techniques today available to the scientists working with particle accelerators, a suitable method of beam monitoring to establish spatial position and intensity remains a problem. The present-day techniques of current monitoring are well known and the disadvantages of using autoradiographing techniques or intercepting detectors are familiar. The paper that follows describes a beam position sensor that can be used to establish the spatial position of a pulsed accelerator beam; associated with this system is a current transformer used to produce the beam pulse for amplitude-time analysis and current integration. The sensor and current transformer have been used on a variable energy (5-18 MeV) electron linear accelerator for about one year and recent work indicates the feasibility of using the position sensor technique with an external cyclotron beam.

The electromagnetic properties of an accelerator beam can be used to locate its electrical center. Two systems of detection have been considered. The first consisted of determining the induced charge on an array of induction electrodes positioned in close proximity to the beam. Such a system is rather poor in signal strength, and it is the purpose of this writing to describe the second system, a magnetic induction technique.

2. Theory

The voltage induced in a coil with its axis in a plane normal to the direction of a long current filament but displaced a fixed distance, is given by

$$e = - \frac{\partial \phi}{\partial t} = \frac{-2\mu AN}{r} \frac{\partial}{\partial t}$$

where ϕ is the magnetic flux linking the coil, A the effective cross-sectional area of the coil, N the total turns of the coil, μ the effective permeability of the coil-filament flux loop, r the effective distance from the current filament i to the axis of the coil, and t the time.

If two identical coils are symmetrically positioned about the current filament with their axes in a plane perpendicular to the filament, then, each will indicate induced voltages of equal magnitude. When the current filament is displaced, the induced coil voltages will no longer be equal. Connecting the two coils in series opposition will result in a voltage e_1 which can be used to determine the magnitude and direction of the spatial shift of the current. That is,

$$e_1 = e_{r_1} - e_{r_2} = K \frac{\partial i}{\partial t} \left(\frac{1}{r_1} - \frac{1}{r_2} \right),$$

where $K = -2\mu AN$.

If the current filament is displaced an incremental distance Δr from the midpoint (central axis) of the two coils, one has

$$r_1 = r \pm \Delta r,$$

and

$$r_2 = r \mp \Delta r.$$

† Based on work performed under the Auspices of the U.S. Atomic Energy Commission.

Neglecting second order terms in Δr and considering only the time derivative of the current, then, the signal is approximately

$$e_1 = \pm K_0 \Delta r \frac{di}{dt}, \quad (1)$$

where $K_0 = -4 \mu AN/r^2$. For small displacement distances, the signal e_1 will be directly proportional to the distance the current filament is displaced from the central axis of the coils. The polarity of the signal ($\pm$) will be dependent upon the displacement direction. It is this principle which has been used to develop the beam position sensor.

To utilize the voltage e_1 , the sensor was designed to operate as a series resonant circuit, fig. 1, with the output signal e_2 being the voltage drop across

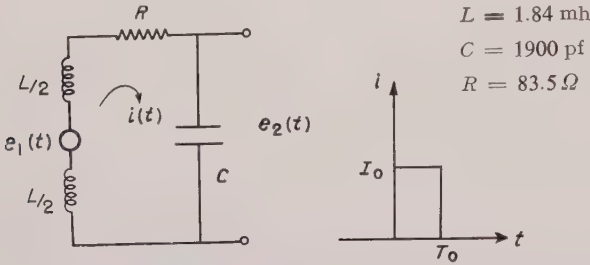


Fig. 1. Equivalent electrical circuit of the linac beam pulse sensor and assumed accelerator beam pulse shape.

the equivalent circuit capacitance. For the ANL linac, the beam current pulse appears as a non-periodic driving function; the period of the beam pulses is a minimum 2.5 ms (400 pps—maximum repetition rate) and the time constant of the sensor circuit is about 0.04 ms. The cyclotron beam is of a different character, and must be considered as a periodic driving function; the period of the beam pulses is about 0.09 μ s and the time constant of the circuitry is about 2 μ s. For the following analysis, only the linac beam pulse will be considered.

Referring to fig. 1, the output signal $e_2(t)$ can be determined by Laplace transformation techniques. Assuming a rectangular current pulse envelope, such an analysis gives

$$e_2(t) = \frac{K_0 I_0 \Delta r}{LC(s_1 - s_2)} \left[e^{s_1 t} - e^{s_2 t} + \left(-e^{-s_1(t-T_0)} + e^{-s_2(t-T_0)} \right) U(t - T_0) \right]$$

where T_0 is the length of the beam pulse, and $U(t - T_0)$ is a unit step function initiated at time $t - T_0$. Since the circuit is designed to be oscillatory, then

$$s_1 = \alpha + j\beta \quad \text{and} \quad s_2 = \alpha - j\beta;$$

where

$$\alpha = -R/2L, \text{ and } j\beta = \left[\left(\frac{R}{2L} \right)^2 - \frac{1}{LC} \right]^{1/2}.$$

Substituting for s_1 and s_2 , the output signal

$$e_2(t) = \frac{K_0 I_0}{LC\beta} \Delta r \left[\sin \beta t e^{-\alpha t} - \sin \beta (t - T_0) e^{-\alpha(t-T_0)} U(t - T_0) \right].$$

For a centrally located beam, the signal voltage $e_2(t)$ is zero, but for a beam displacement Δr , the signal is a composite of two functions. In examining equation (2), it can be seen that the function

$$\frac{K_0 I_0}{LC\beta} \Delta r \sin \beta (t - T_0) e^{-\alpha(t-T_0)} U(t - T_0)$$

becomes effective at the end of the pulse, i.e., $t = T_0$. The effect of this function can be eliminated by restricting the signal data to a time interval $\leq$ the pulse length T_0 . Then, the function

$$\frac{K_0 I_0}{LC\beta} \Delta r \sin \beta t e^{-\alpha t}$$

becomes the signal from which displacement data is obtained. If the circuit is designed so that the maximum amplitude of the first excursion of oscillation occurs within the time T_0 , then the amplitude and phase ($\pm$) can be used as a direct measure of beam displacement and will be independent of beam pulse length. This condition will be satisfied if the natural angular frequency of the sensor circuit is $> \pi(2T_0)^{-1}$.

To determine the displacement, of the beam from the maximum amplitude of the first excursion, the parameters of the amplitude must be established. For example, the peak current of the pulse I_0 , is established by the calibrated current transformer close coupled to the position sensor and

stants K_0 , L , C , β , and α are the design parameters of the system.

Construction

The construction of the position sensor for the electron linear accelerator was predicated by the factors of eq. (2), and the physical requirements imposed by targetry and the distance separating

No. 28 formax-insulated wire wound on a 1.2 cm O.D. $\times$ 3.8 cm long ferrite core. The effective permeability μ with all coils in position, is 3.9×10^{-6} henry/meter. The effective inductance and capacitance of a coil set, including cable, is 1.84 mH and 1900 pF respectively.

The two coils of a coil set, such as AA', are connected in series opposition, with the two output

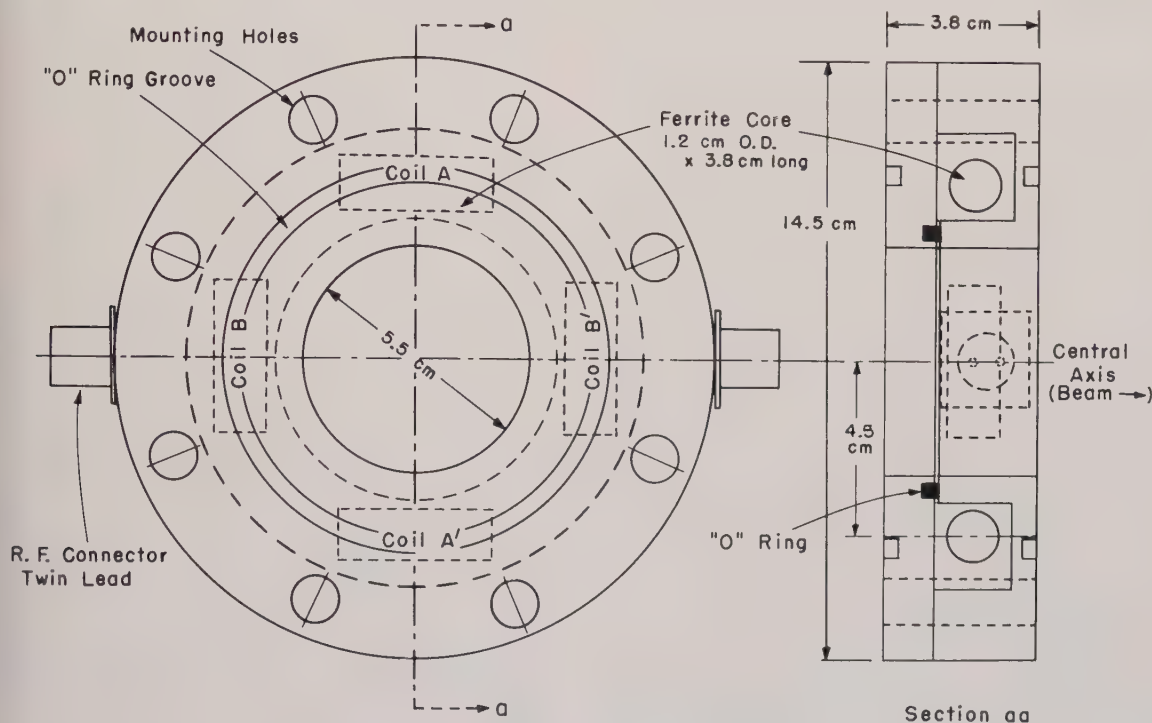


Fig. 2. Mechanical schematic of the linac beam position sensor.

the coils from the information "read out" location. The sensor was constructed with mechanical simplicity to prove the feasibility of such a unit. Referring to fig. 2, it is seen that the coils are housed within a metallic shell and are excluded from the vacuum system by means of an "O" ring. This "O" ring seal also breaks the conducting path of the inner surface thereby permitting magnetic field coupling between the beam and the coils. The outer surface of the shell mechanically and electrically connects to the beam tube of the accelerator. Aluminum was used in the construction of the shell.

The sensor coils, 4 in number, are placed as indicated in fig. 2. Each coil consists of 275 turns of

leads terminated in a twin coax cable connector. A cable distance of 120 feet exists between the sensor and the information display station. At the receiving end of the cable, the signal is introduced into a commercial type differential amplifier with its output terminal connected to a display oscilloscope†. The effective voltage gain of this amplifier system is 90. A selection switch is used for choosing the display of either the horizontal or vertical displacement signal.

Referring to eq. (2), the parameter β is established by the minimum beam pulse length and the length of coaxial cable required to bring the signal from the detector to the display oscilloscope. For

† Tektronix, Incorporated, Portland, Oregon.

the described system, the minimum beam pulse length was set at $3 \mu\text{s}$, and β was chosen to be 0.54×10^6 radians/second. The sensor coils were constructed to resonate with the capacitance of the cable (RG22B) at a frequency of about 86 kc/s.

The parameter α is established by the effective inductance and resistance of the system. No special precaution was taken to obtain a minimum value.

A current pulse transformer is used to measure the linac current, i.e., parameter I_0 . The first test unit was a commercial product, but its physical size limited its use. This motivated the construction of a transformer with a toroidal ferrite core of 3.2 cm I.D. and 1.6 cm square cross section. Standard construction techniques were used, with the core material being Ferroxcube No. 4A[†], and the total number of conductor turns being 100. The external shell is similar to that of the position sensor, i.e., transformer external to the vacuum system but within the outside conducting sheath. The physical size is about 11 cm O.D. with an over-all length of 5 cm.

The over-all length of both the sensor and transformer is about 9 cm, with a beam aperture of 5.5 cm and a maximum O.D. of 14.5 cm.

4. Experimental Results

The lumped parameters of the equivalent circuit, fig. 1, were bench-determined by standard electrical measurement techniques. To bench test the position sensor and current pulse transformer, the linac beam was simulated by using a voltage generator with a $5 \mu\text{s}$ output pulse feeding a single conductor terminated in a 50 ohm resistor to ground. The single conductor, threading the beam aperture of the two units, was used as a current filament to establish sensitivity and the characteristics of the output signal of both the sensor and transformer. Upon completion of the bench tests, the sensor and transformer were coupled to the target tube of the linear accelerator for beam calibration data and operating experience. It is to be noted that the beam test location was adjacent to the accelerator's radio-frequency system and no extraneous noise signals were experienced.

The calculated output voltage function, $e_2(t)$, for

[†] Ferroxcube Corporation of America, Saugerties, New York.

a beam displacement of 0.5 cm, a peak current of 100 mA and a pulse length of $5 \mu\text{s}$ is given by fig. 3. The corresponding signal obtained from acceleration

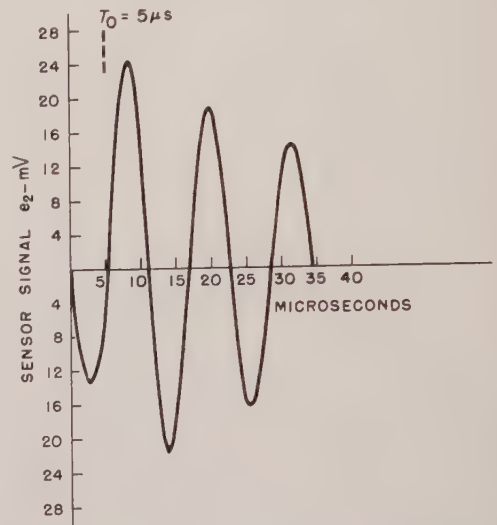


Fig. 3. Calculated linac sensor signal for a beam pulse of 100 mA, $5 \mu\text{s}$ duration, and a displacement of 0.5 cm.

tests is given by the oscilloscope trace of fig. 4. The 13 mV amplitude of the first excursion and the 86 kc/s oscillation frequency are in excellent agreement with calculations.

The dependence of sensor output signal on beam position was determined by displacing the 1 cm diameter accelerator beam from the central axis and allowing the projectiles to irradiate a copper

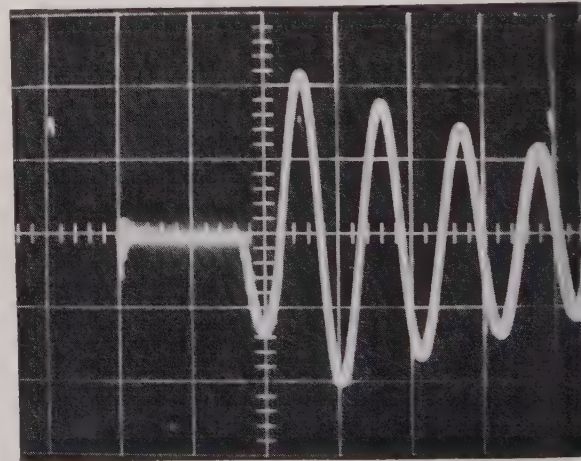


Fig. 4. Linac sensor signal as displayed on oscilloscope. Beam parameters identical to conditions of fig. 3. Horizontal and vertical coordinates are $10 \mu\text{s}$ and 10 mV per large division respectively.

target. The induced target activity was autoradiographed and the beam displacement measured. Fig. 5 is a compilation of displacement thus measured and output sensor voltage (maximum amplitude of the first excursion of the oscillation) data. The measured sensitivity of a coil set, horizontal or vertical, is about 15.5 mV/cm-100 mA as compared to a calculated value of 15.0. Varying the length of the beam pulse showed that the

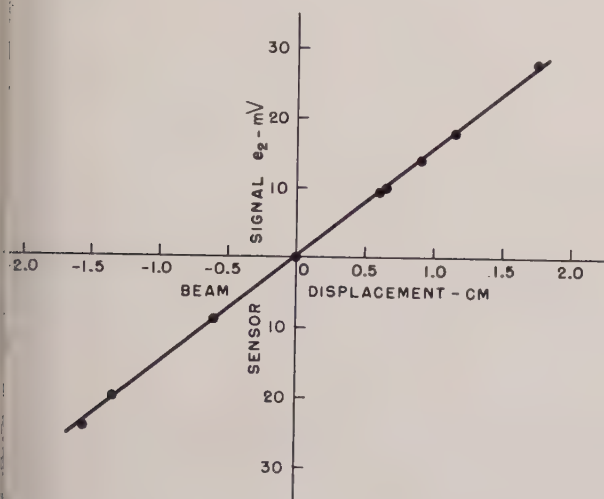


Fig. 5. Measured sensor signal, peak amplitude of first oscillation excursion, versus beam displacement. Resulting sensitivity is 15.5 mV/cm-100 mA.

sensitivity was independent of pulse length for $\tau \geq 3 \mu\text{s}$; based upon design constants, this limit is $2.9 \mu\text{s}$.

After the completion of the accelerator calibration tests and the gathering of operating data, the coils of the sensor were wound around a higher permeability ferrite. The material first used was of unknown character, but the latter was antenna rod ferrite, type Q-1†, of a permeability of about 400. The use of this material increased the sensitivity by a factor of two, i.e., 31.0 mV/cm-100 mA. For the given geometry a further increase in the permeability of the material will not greatly enhance the signal output.

Since this report is not primarily concerned with the construction and test of current pulse transformers, it will only be stated that, the measured sensitivity of the constructed unit was 1.0 V/A with about 0.4% signal drop per microsecond.

5. Conclusion

For a peak current of 100 mA, sensitivity about 30 mV/cm-100 mA, the sensor and oscilloscope detector can be used to spatially locate the charge center of a beam to about 0.5–1 mm. If used as a null detector to centrally position the beam, the accuracy of positioning can be increased.

To decrease beam pulse length and maintain sensor signal independence, the parameter β must be increased so that $\beta \geq \pi/2T_0$. Such an increase can be accomplished by reducing either L or C or both. In making these changes, it is to be recognized that the amplitude of the output signal is proportional to $N(LC\beta)^{-1}$ or $C^{-1/2}$; assuming $\beta = (LC)^{-1/2}$ and L is proportional to N^2 . Thus, changing the inductance will not decrease the sensitivity but if C is decreased, the sensitivity will increase by the factor $(C/C_0)^{1/2}$, where C and C_0 are the new and old values of capacitance respectively.

The sensor system was designed for an oscillatory condition to realize maximum sensitivity, and to facilitate detection and ease of measuring beam displacement. The sensitivity of both the horizontal and vertical position sensors are now 15.5 mV/cm-100 mA for a beam aperture of about 5.5 cm. This sensitivity can be increased to 31 mV/cm-100 mA by using the type Q-1 ferrite, or equivalent. Further increases could be effected by making several other changes. The first would be to decrease the cable capacitance, i.e., by changing from an RG22B type cable (16 pF/ft) to an RG24A (12 pF/ft). This would increase the sensitivity to about 35 mV/cm-100 mA. Cable length could also be decreased and a preamplifier used, but of course, this would depend upon the accelerator installation and associated requirements. Bench measurements indicate that if the inner surface of the sensor shell is an insulator instead of a conductor, the sensitivity would be increased by a factor of two. A factor increase of about 4.5 could be realized by decreasing the beam aperture to 2.5 cm. If these changes are made, it is expected that the sensitivity of the sensor would be about 330 mV/cm-100 mA.

In addition to increasing sensitivity, the method of data "read out" could be improved by replacing the oscilloscope detector by a peak reading circuit

† General Ceramics Corporation, Keasbey, New Jersey.

gated to the first signal excursion. It is to be realized that the sensitivity of the described unit was quite adequate for the irradiations performed and the system was kept simple by using a minimum of components.

The results of test and operating experience have shown that the described current transformer-beam sensor system permits the electron linear accelerator operator-experimenter to integrate the charge to the target and to be assured that the beam center is "on target" without the use of collimating slits or current intercepting detectors. Such a technique could in general be quite useful for other electron or heavy ion linear accelerators.

Work has been initiated on a beam position sensor to be used with the external beam of the ANL 60 inch cyclotron. Adapting the sensor technique to a cyclotron beam is difficult because of the lower peak pulse intensity and the higher repetitive frequency of the beam pulses. For this type accelerator, the beam pulses must be considered as a periodic driving junction. A Fourier analysis of an assumed rectangular beam pulse shape shows that the amplitude of the first few harmonic components are approximately equal to the amplitude of the fundamental. Thus, the sensor can be tuned to a frequency greater than the fundamental, i.e., to the second or third harmonic.

Construction of the first test unit followed the general design of the linac sensor. The aperture of the beam tube is 5 cm and air-core coils were used for the lack of suitable ferrites. The circuit was tuned to the fundamental operating frequency of 11.2 Mc/s. For initial tests, the unit was used only as a null type indicator with the sensor signal directed into a close coupled differential preamplifier and then cabled out to a communication receiver. Such an arrangement did not indicate the direction of displacement but did prove that a time averaged beam of $0.1 \mu\text{A}$ could be centrally located to a few millimeters. Work continues in the direction of increasing detection sensitivity by using ferrites, and improving coil and shell geometry.

In writing this paper it came to our attention that work of this general nature had been accomplished and reported by I. A. Grishaev¹⁾ for linac operation. Since the techniques were significantly different, it was decided that the above work should be reported.

Acknowledgements

The authors wish to acknowledge the assistance of G. W. Parker for the mechanical design of both the linac and cyclotron position sensors.

¹⁾ I. A. Grishaev, N. I. Mocheshnikov and V. F. Ivanov, Instr. and Exp. Techniques 4 (1961) 537.

A TIME-OF-FLIGHT SPECTROMETER FOR FAST NEUTRONS

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Part 1 a time-analyzer for the nanosecond range with correction of the amplitude-effect in the start channel is described. The output of an ELDORADO^{††} time-to-pulse-height converter is corrected by adding a signal depending on the amplitude of the start pulse. Using two 56-AVP phototubes and 102 plastic scintillators (42 mm diameter, 25.4 mm length) the half-width of a prompt Co⁶⁰ γ - γ coincidence curve was found to be 6.5×10^{-10} s. The variation of the time resolution in a start-level range from 150 keV to 900 keV electron energy was less than 1×10^{-10} s. In order to increase the detection efficiency of the time analyzer for applications in neutron spectroscopy the 56-AVP in the start channel was replaced by the

larger tube 58-AVP (NE-102, 125 mm diameter, 25.4 mm length), and a resolution of 8×10^{-10} s was obtained at a start-level of 70 keV.

In part 2 a new method of producing ion-bursts in the nanosecond range is described. The deuteron beam of a Duo-Plasmatron is periodically defocused by means of a 4 Mc/s HF-generator modulating the extraction voltage of the ion-source. By proper adjustment of the geometry and the HF-amplitude, time focusing on the target is achieved. By this method much more intense ion-bursts can be achieved than by the conventional beam-chopping. Peak currents of 3 mA were realized with a burstwidth of 3 nanosecond (ns).

PART I

AMPLITUDE-CORRECTED TIME ANALYZER IN THE NANOSECOND RANGE

Introduction

The time-of-flight method is often used in the spectroscopy of fast neutrons. In the course of time many types of time-analyzers have proved to be very convenient: the "time-to-pulse-height converter" and the "vernier chronotron"^{1,2,3}). If triggered by fast pulses of a mercury-switch generator, both can give an intrinsic resolution of the order of 10^{-10} s. In most experiments, however, the time-analyzer is started by the pulses of a photomultiplier. Depending on the experimental setup, information in the stop-channel can be a normalized reference (e.g. time-of-flight method using a pulsed source) or also a signal from a phototube (detection of recoil particles, fission products, or correlated radiation). The intrinsic resolution is broadened now as a result of statistical fluctuations of the light emission in the scintillator,

transit-time spreads in the phototube, and time-shifts caused by the variation of signal amplitude in start and stop channel. This "amplitude-effect" can seriously deteriorate the time resolution, especially in low-biased detection of fast neutrons. By knowing the characteristic of this effect, however, one can greatly reduce its influence, as will be shown in this work. In our experiments of fast neutron scattering on heavy nuclei, the time-analyzer must fulfill the following requirements:

time-range	0-200 ns
time-resolution	1 ns
bias in start-channel	300 keV proton energy
phototube in start channel	Philips 58-AVP with 125 mm diameter NE-102 scintillator
high linearity and sufficient long term stability.	

¹) Weber, Johnston and Cranberg, Rev. Sci. Instr. **27** (1956) 166.

²) H. W. Lefevre and J. T. Russel, Bull. Am. Phys. Soc. **2** (1957) 175.

³) H. W. Lefevre and J. T. Russel, IRE Trans. on Nucl. Sci. NS-5, (1958) 146.

[†] On leave from the Instytut Fizyki Jadrowej w Krakowie, Poland.

^{††} Eldorado Electronics Company, Oakland, California, Model TH-300.

The method of time-to-pulse-height conversion used in the Los-Alamos converter now commercially available (Eldorado Electronics) was considered most suitable.

2. Amplitude-Effect and its Correction

Variation in the amplitude of the start- and stop-signals limits the time resolution. As the amplitude of the start-pulse decreases, the start-discriminator is triggered later. Such a low signal will therefore start the converter too late relative to the normalized stop-signal and consequently the amplitude of the output signal is reduced. This difficulty may be corrected by adding a suitable signal to the low output pulses. The amplitude of the correction-signals increases as the amplitude of the start pulse decreases†. A block diagram of our correction device is shown in fig. 1. In the first stage, pulses arriving from the side channel amplifier are shaped and, if necessary, attenuated. A reference generated by the converter when started is fed to a second input and the difference of these two pulses is taken. The information needed for correction appears at the

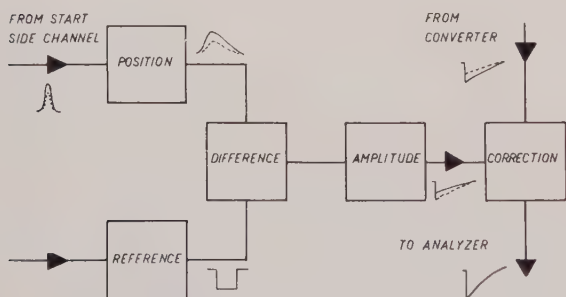


Fig. 1. Block diagram of the correction device.

output of this stage and determines up to which amplitude corrections shall occur. Only negative signals are allowed to the next stage (by means of a biased diode), where continuous variation of the correction amplitude is provided. The last stage adds the correction to the pulse arriving from the converter and feeds it to the pulse-height analyzer.

Fig. 2 shows schematically the operation of the correction device on a prompt coincidence curve corresponding to the time t_0 . It was assumed that

† This principle has already been used by D. Maeder to correct a time-analyzer⁴).

there was no amplitude effect in the stop channel. The long tail on the left side is caused by the small signals in the start channel. The dashed part of the

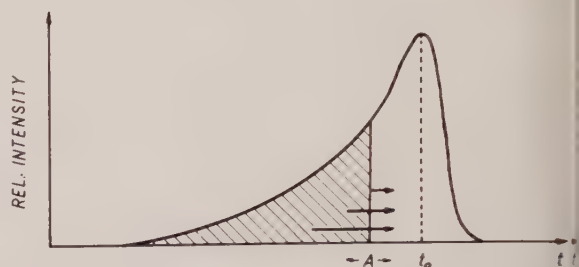


Fig. 2. Prompt coincidence line corresponding to the time t_0 . The correction of the amplitude effect is shown schematically by the arrows.

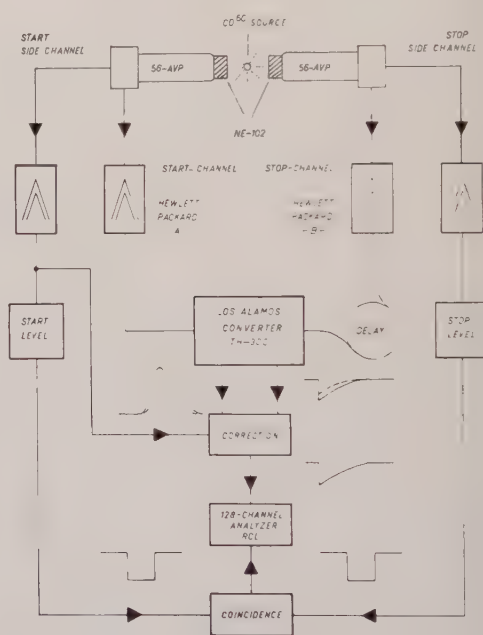


Fig. 3. Block diagram of the time-analyzer.

time distribution is under correction; the point may be chosen by the position stage. The arrows indicate the shift caused by the correction process. The amount of this shift can be selected by changing the attenuation in the amplitude stage.

3. Time-Analyzer

Co^{60} γ - γ coincidences were used to test the time-analyzer. Fig. 3 is a schematic drawing of the

⁴) J. H. Neiler, Proc. of the second Symp. on Advances in Fast Pulse-Techniques for Nucl. Counting, Berkeley, CA, UCRL-8706 (1959) p. 60.

arrangement. $200\ \Omega$ coaxial cables connect the plate of the start multiplier (working resistor $200\ \Omega$) to a Hewlett Packard type A amplifier, which in turn is connected to the start input of the converter. The converter requires a stop amplitude of at least 15 V , the stop channel (starting from the 14th node of the stop multiplier) was equipped with a Hewlett Packard type B amplifier. $200\ \Omega$ cables of variable length are inserted in the stop line to give controlled delay. The slow side channels (originating from the 12th dynodes of the respective multipliers) bring the amplitude information to the side channel amplifiers after passing cathode followers. Energy selection is made by two EFP-60 discriminators. The width of the output pulses is chosen to give coincidence if they are at most 250 ns apart. The coincidence pulse opens the gate of the pulse-height-analyzer. The start multiplier signals are brought from the start side channel to the correction device by means of a $75\ \Omega$ line.

Results

The effect of the amplitude correction device is shown in fig. 4 and 5. The influence of the "Position" and the "Amplitude"-stage on the half-width of a prompt $\text{Co}^{60}\ \gamma\text{-}\gamma$ coincidence line is shown in fig. 4. Both curves show pronounced minima and determine the optimal conditions at which the correction device should work.

The time resolution of our amplitude-corrected analyzer as a function of the start level is shown in fig. 6 together with the results of other authors. The different size of the scintillators is to be noticed. The method we describe can of course be used in the stop channel too, but this is of less interest in our case, because our reference signal in the stop-channel has relatively little amplitude variation.

The integral linearity of the time analyzer was measured by insertion of delay cables of variable length in the stop channel. Using a mercury-switch generator with two outputs, the linearity was better than 1% over a time-range of 180 ns .

Appendix to Part I

TIME RESOLUTION OF A TIME-ANALYZER

E. Gatti and V. Svelto⁸⁾ introduced four methods for processing the output pulse of the phototube and

calculated the time variance of the apparatus due to:

a) statistical fluctuations in the emission of the photoelectrons, spread of the photoelectric yield and spread in the gain of the tube;

b) spread in the overall transit-time⁹⁻¹²⁾, and

c) spread in the "single-electron-response".

Further they give the total time variance for the fixed parameters $\tau_F/\epsilon_{PH} = 2$ and $\tau_F/\epsilon_{PH} = 6$ where τ_F is the decay-time of the fluorescence and ϵ_{PH} is the rms variation in the transit time through the tube¹³⁾. In the case where the time-analyzer is started when a definite number of electrons corresponding to C photoelectrons is collected at the anode of the multiplier, the time variance shows pronounced minima as a function of C/R , where R is the total number of photoelectrons of the pulse. Several curves are given with the parameter λ/ϵ_{PH} where λ designates the root-mean square width of the "SER".

In our case, assuming the values

$$\tau_F = 3.5 \times 10^{-9}\text{ s} \quad (\text{NE-102})$$

$$\epsilon_{PH} = 0.9 \times 10^{-9}\text{ s} \quad (\text{full cathode})$$

$$\lambda = 0.9 \times 10^{-9}\text{ s}$$

$$R = 500 \text{ photoelectrons (1 MeV } \beta)$$

$$C = 25 \text{ photoelectrons (50 keV } \beta)$$

we obtain

$$\tau_F/\epsilon_{PH} = 4$$

$$\lambda/\epsilon_{PH} = 1$$

$$C/R = 0.05.$$

Unfortunately curves are not given with the parameter $\tau_F/\epsilon_{PH} = 4$, so we can give only a rough estimate of our time-variance ϵ_t^2

$$\epsilon_t^2 = x \frac{\tau_F \cdot \epsilon_{PH}}{R} = x \times 0.63 \times 10^{-20}\text{ s}.$$

⁸⁾ E. Gatti and V. Svelto, Nucl. Instr. and Meth. **4** (1959) 189.

⁹⁾ G. Pietri, Proc. of the International Symposium on Nuclear Electronics, Paris, 1958) p. 57.

¹⁰⁾ Y. Koechlin, Proc. of the International Symposium on Nuclear Electronics, Paris (1958) p. 67.

¹¹⁾ G. Pietri, Proc. of the Second Symposium on Advances in fast Pulse Techniques for Nuclear Counting, Lawrence Radiation Laboratory, Berkeley, 1959, p. 20.

¹²⁾ M. Barbier, CERN-Report 60-34 (1960) 11.

¹³⁾ J. H. Neiler and W. M. Good, Fast Neutron Physics, Part I (Interscience Publishers Ltd., New York, 1960) p. 561.

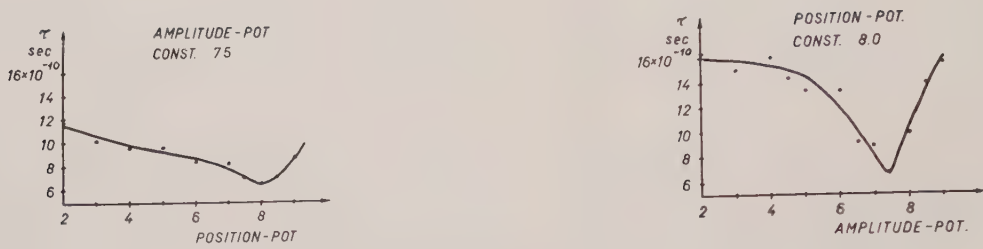


Fig. 4. Influence of the "Position" and the "Amplitude"-stage on the time resolution.



(a)

(b)

(c)

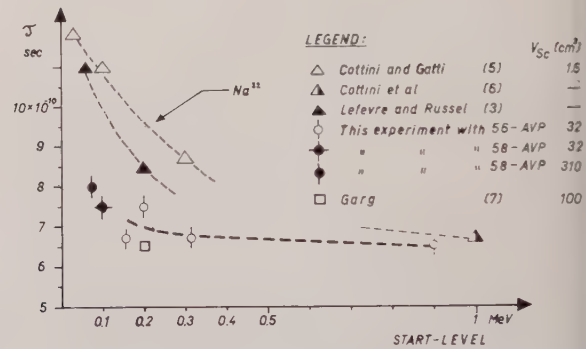


Fig. 6. The time resolution of different time-analyzers as a function of the threshold in the side channels. τ is the half width of a prompt Co^{60} γ - γ coincidence curve, with the exception of the points due to Cottini and Gatti, where the γ -radiation of Na^{22} was used. (Refs. ^{5,6,7}.)

Fig. 5. a) shows a prompt Co^{60} γ - γ coincidence line without an selection of energy in the side channels and without amplitud correction. The channel width is 1.15×10^{-10} s. b) shows the same time-spectrum with the correction device switched on or c) illustrates the influence of the energy-selection in the side channels (threshold about 100 keV electron energy) with correction on. The accumulation time of the RCL-pulse-height analyzer was the same for the three spectra.

⁵) C. Cottini and E. Gatti, Nuovo Cim. 4 (1956) 1550.
⁶) C. Cottini *et al.*, Proc. of the Second Symp. on Advances in Fast Pulse Techniques for Nuclear Counting. Berkeley, Calif. UCRL-8706 (1959) p. 49.
⁷) J. B. Garg, Nucl. Instr. and Meth. 6 (1960) 72.

From the graphs of E. Gatti and V. Svelto with $\epsilon_{PH} = 6$ we see, that $x \approx 5$ and obtain a total time-variance of

$$\epsilon_t \approx 1.8 \times 10^{-10} \text{ s.}$$

Assuming two phototubes (start and stop chan-

nel), we now calculate the half-width of a prompt coincidence curve to be

$$H = 2.36 \times \sqrt{2} \times \epsilon_t = 6 \times 10^{-10} \text{ s,}$$

which is in good agreement with our experimental resolution of $6.5 \times 10^{-10} \text{ s}$ (see fig. 6).

PART II

PRODUCTION OF ION-PULSES IN THE NANOSECOND RANGE BY TRANSIT-TIME MODULATION

Introduction

The well known method of beam chopping^{14,15,16}) has two limitations: By increasing the writing speed to shorten the ion bursts, the peak current available at the target is reduced in proportion to the duty cycle. This difficulty may be eliminated by the use of a Duo-Plasmatron ion source; short pulses of high intensity, however, are lengthened by space charge forces as they travel through the accelerator. According to R. J. Connor¹⁷) a 10 ns pulse is limited to 1–2 mA in practice. To produce shorter bursts of ions with greater intensities one of the following methods has been used: In the Mobley¹⁸) magnet buncher the beam is swept across the entrance of a magnet in a manner causing the leading ions to take longer paths through the magnetic field than the trailing ions, thereby time focusing the pulse at the target. Klystron bunching^{19,20}) makes use of a rising voltage across a bunching gap, speeding the trailing ions of the first up and bringing them to a time focus at the target. A disadvantage of this method is its introduction into the beam of a time correlated variation in energy, which may be neglected, however, depending on its magnitude and on the experiment. Looking for a simple combination of chopping and bunching, we came to the solution now described, which makes use of only one HF-generator to produce and bunch the ion bursts. The required RF-amplitude is low enough to make the energy spread introduced in the beam negligible for the production of neutrons by the (d, d) and (d, t) reactions.

2. Method

The general experimental arrangement is shown in fig. 7. Ions are generated in a Duo-Plasmatron²¹) ion-source and extracted by means of a voltage modulated with 4 Mc/s. The d.c. component ($U_0 = 30 \text{ kV}$) of this extraction voltage is fed over a series resistor to the focusing electrode (Einzel-lens). This

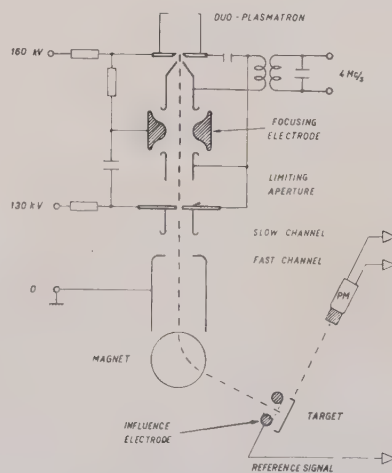


Fig. 7. schematic view of experimental setup. The diameter of the limiting aperture is 5 mm.

¹⁴) C. W. Snyder and V. E. Parker, Phys. Rev. **95** (1954) 635 A.

¹⁵) L. C. Cranberg and J. S. Levin, Phys. Rev. **103** (1956) 343.

¹⁶) C. Turner, Rev. Sci. Instr. **29** (1958) 480.

¹⁷) R. J. Connor, Nucl. Instr. and Meth. **11** (1961) 122.

¹⁸) P. C. Mobley, Phys. Rev. **88** (1952) 360.

¹⁹) M. P. Nakada, V. J. Ashby, M. Harris and W. Klein, Bull. Am. Phys. Soc. II, **1** (1956) 69.

²⁰) J. H. Neiler and W. M. Good, Fast Neutron Physics, Part I (Interscience Publishers Ltd., New York, 1960) p. 542.

²¹) P. Huber, C. Poppelbaum und R. Wagner, Helv. Phys. Acta **33** (1960) 564.

resistor is chosen to focus the beam at the limiting aperture for a given ion current and extraction voltage U_0 . The ions are accelerated to 160 kV,

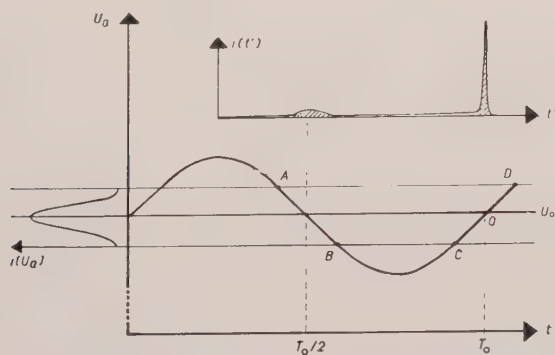


Fig. 8. Current as a function of the extraction voltage and time.

pass an analyzing magnet and strike a tritium target after generating a reference signal on a ring by induction charge. The principle of burst production is shown in fig. 8.

At the time of the zero transition of the HF the beam is focused at the limiting aperture. The beam is broadened as the extraction voltage changes. This results in the curve $i(U_a)$ in fig. 8, showing the dependence of current passing the aperture from the extraction voltage. Note that beam divergence increases to such an extent during the linear part of the HF that the current passing the aperture becomes negligible when the limits given by A and B in fig. 8 are reached. Bunching occurs during this linear part as the extraction voltage passes through U_0 : ions leaving later have a relatively higher energy (0, T_0 in fig. 8). On the other hand a decreasing voltage around U_0 ($T_0/2$ in fig. 8) causes earlier particles to have a higher energy (debunched pulse) and thus the target current is expected to look like $i(t')$ in fig. 8. The HF-amplitude is chosen for optimum time-focussing at the target. The limitations introduced by the debunched pulse will be discussed later. Considering that a modulation of the extraction voltage also modulates the voltage between extracting and focusing electrodes, one finds that the bunching effect can be reinforced by setting the transit time for this distance equal to $T_0/2$. This results in a reduction of required HF-amplitude.

3. Results

In passing through a ring directly above the target, the ion pulse induces a signal that can be used as a control of burst production and which is taken as a zero-time marker in the time-of-flight experiments. This signal is shown in fig. 9 after amplification by two Hewlett Packard type A amplifiers. The differential linearity of the time analyzer, which is given in fig. 10, was measured using the signals of a Co^{60} source in the start channel and the reference signals induced by the deuteron bursts in the stop channel. To avoid a synchronous background, no target was used during this measurement and the distance between the start phototube and the accelerator was about 8 m. Further the neutron detector was shielded with paraffin against the d-d-neutrons from targets generated by the beam itself.

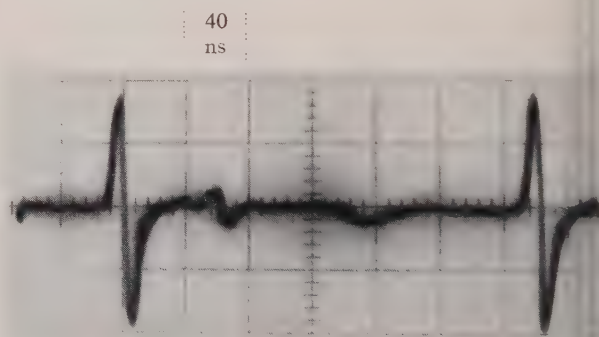


Fig. 9. Reference signals from the influence electrode. Abscissa 40 ns/cm, ordinate 2 V/cm.

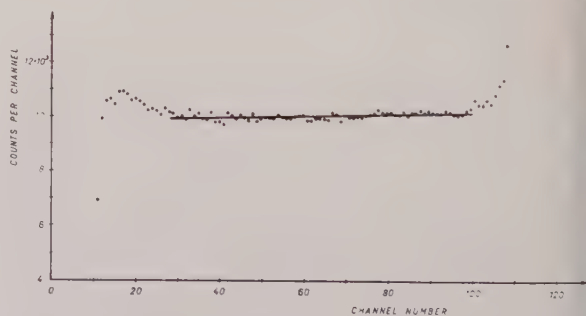


Fig. 10. The differential linearity of the time analyzer. Over a time range of 160 ns, the linearity is about 2%. Channel width 2.25 ns/channel.

Fig. 11 illustrates the resolution of the spectrometer. The width at half value is seen to be about 3.5 ns. Average target current being 50 μA , the

improvement relative to the earlier method²²⁾ of beam sweeping is 60% in resolution and 600% in the intensity of the bursts. Neutrons originating

$T_0/2 = 125$ ns. With a flight path of 1.7 m, neutron spectra of 1–14 MeV neutrons are unaffected by the debunched bursts. If a bigger time interval is desired, synchronous sweeping of the beam can be used to keep the debunched bursts from striking the target. The use of a higher extraction voltage is expected to bring improved resolution by further reducing the space charge effects.

Acknowledgements

For many helpful and valuable discussions we are greatly indebted to Professor E. Baldinger and Dr. W. Czaja. We wish to express our thanks to Mr. H. Weyeneth for constructing the Duo-Plasma-tron and to Mr. F. Abt for having built part of the electronic equipment. We also wish to acknowledge the help of Dr. L. Brown in preparing the text. One of us (Z.L.) wishes to express his gratitude to the International Atomic Energy Agency for a fellowship enabling him to participate in this work.

Fig. 11. Time-of-flight spectrum of 14 MeV neutrons on a RCL 256-channel analyzer. Channel width: 0.8 ns/channel.

from the debunched ion pulse are observed, the distance to the peak of bunched ions is of course

²²⁾ P. Niklaus, P. Huber and R. Wagner, *Helv. Phys. Acta* 34 (1961) p. 520.

EXPERIMENTAL DETERMINATION OF SUMMING DISTRIBUTIONS IN SCINTILLATION DETECTORS

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Received 28 August 1961

A modification of the Hoogenboom summing method has been used to determine the pulse height distribution of summing peaks in NaI(Tl) crystals. The fast coincidence circuit is triggered by time coincident events in two equal crystals and the sum of the two pulses displayed on a multichannel analyzer. These distributions were obtained for a number of standard

sources with two coincident gamma rays and the general features of the shape of the pulse height spectrum are discussed. Moreover, some applications of this method in gamma scintillation spectroscopy are indicated, as for example, the evaluation of the residual summing effect in the analysis of gamma scintillation spectra.

1. Introduction

In scintillation gamma ray spectra it is not unusual to have a summing distribution due to the presence of intense gamma rays in cascade; for instance the transition connecting the second and first excited states and that between the first excited state and the ground state of the product nuclide. Such a summing distribution often hampers the determination of the intensity of weak gamma rays that have an energy inferior or equal to the sum of the two strong transitions. Obviously such summing effects may be minimized by augmenting the distance between source and crystal, but only at the expense of statistical accuracy for the weak gamma rays.

The aim of this work is to show the possibility to determine experimentally such effects for a given geometry; for this purpose a method has been developed which is a modification of the Hoogenboom sumcoincidence set-up¹⁾. The source is viewed by two scintillation detectors of as closely as possible equal characteristics, and the sum of the output signals of the two counters is displayed in a pulse height analyzer subject to the gating condition that there be a time coincident signal from the two detectors. It will be shown that the spectrum obtained in this way represents the shape of the summing distribution that would be observed in the single spectrum from one of the detectors separately.

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2. Experimental Arrangement and Experimental Results

The experimental set-up is shown in block form in fig. 1. Two photomultipliers with NaI(Tl) crystals of equal dimensions (energy resolution equal within 5%) are mounted so as to subtend equal solid angles at the source. Lead shielding is

¹⁾ A. M. Hoogenboom, Nucl. Instr. and Meth. **3** (1958) 57

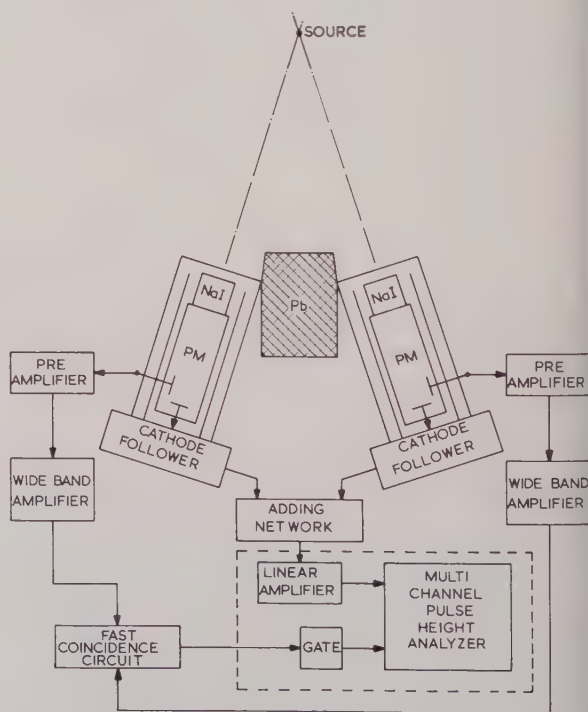


Fig. 1. Block diagram of experimental arrangement.

placed between the crystals in order to eliminate spurious coincidences by Compton events. The pulses from the cathode followers in the photomultiplier anode circuits are fed into a linear adding network; differences in gain between the two detectors are compensated for in this circuit¹).

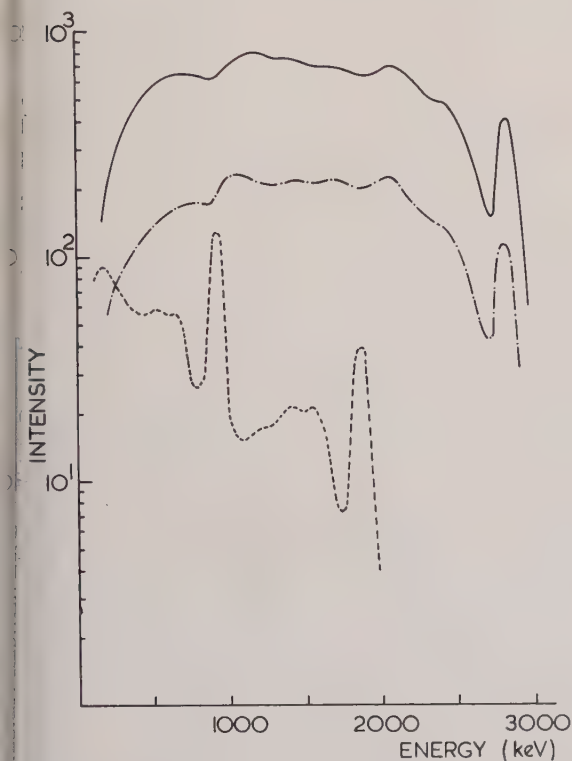


Fig. 2. Experimental sum distribution from ^{88}Y (full curve). Dashed curve: direct spectrum (arbitrary scale). Dot-dashed curve: calculated summing distribution from ^{88}Y .

After amplification the sum pulses are fed into a multichannel pulse height analyzer. The last dynode of each of the two photomultipliers is connected to a preamplifier followed by a wide band amplifier. The output of both amplifiers operates a fast coincidence circuit. The coincidence output is used to gate the sum spectrum in the multichannel analyzer. Then only coincident events in the sum spectrum are selected for storage.

Some standard sources, having two gamma rays in cascade (^{88}Y , ^{60}Co , ^{46}Sc and ^{75}Se), or one gamma ray preceded by positron emission (^{22}Na), were used in order to obtain the desired experimental summing spectra.

In fig. 2 and 3 are shown two typical summing spectra as obtained from ^{88}Y and ^{60}Co . In both figures the direct spectra are also reported for comparison. In fig. 4 the summing distribution is shown from the two annihilation quanta emitted in the decay of $^{62}\text{Zn} + ^{62}\text{Cu}$. For obvious reasons the

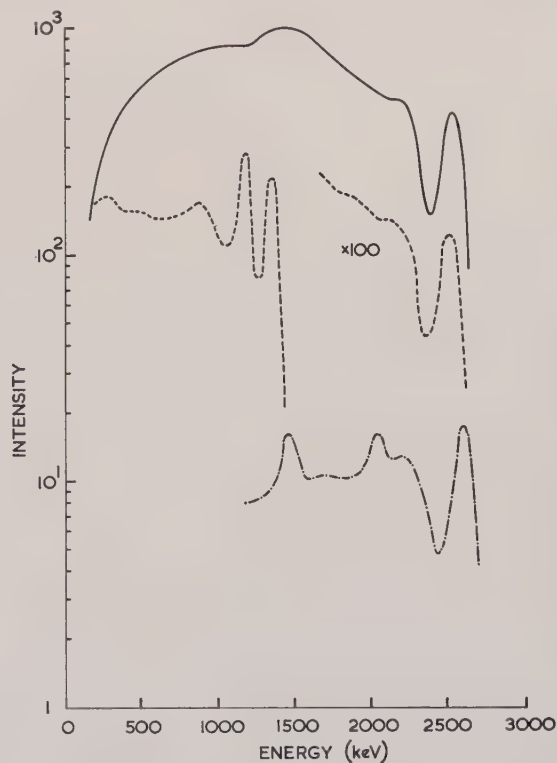


Fig. 3. Experimental sum distribution from ^{60}Co (full curve). Dashed curve: direct spectrum (arbitrary scale) with its associated summing distribution for a $1\frac{3}{4}$ " crystal and a source-detector distance of 7 cm. Dot-dashed curve: spectrum from a single gamma transition of energy approximately equal to the total energy of the ^{60}Co cascade (ThC'' X transition).

two detectors were positioned end-to-end in the last experiment. All spectra were measured by means of two Harshaw NaI(Tl) crystals of 50 mm height and 44 mm diameter, mounted on DuMont 6292 photomultiplier tubes. The half-width (full width at half maximum) of the photopeak of the 662 keV gamma ray of ^{137}Cs as recorded with these counters was 7.9 ± 0.2 and 8.2 ± 0.2 percent, respectively. The sources were located about 7 cm from the faces of both crystals. A lead absorber of 5 cm thickness covered at both sides by 2 mm of copper was interposed between the two crystals in

order to eliminate coincidences due to Compton scattering of one gamma ray from one crystal into the other. The summing distributions were displayed on a RIDL 100 channel pulse height

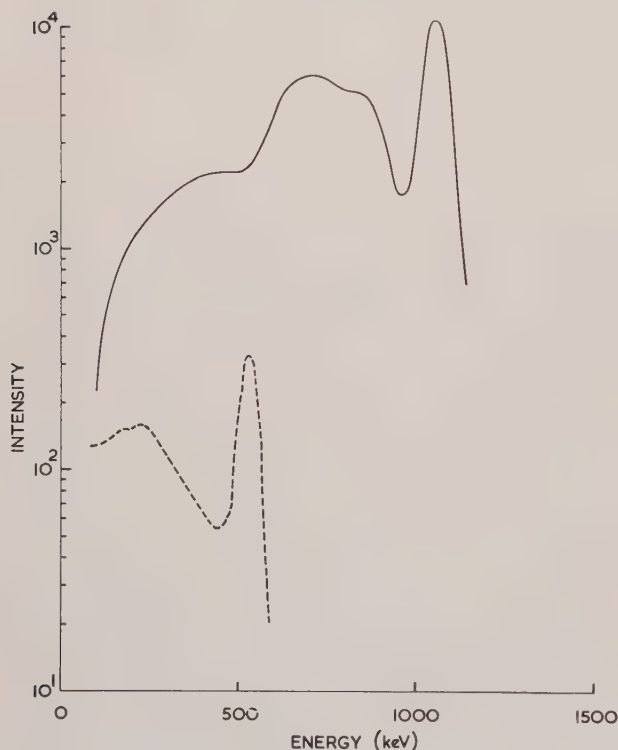


Fig. 4. Experimental sum distribution from $^{62}\text{Zn} + ^{62}\text{Cu}$ (full curve). Dashed curve: Direct spectrum (arbitrary scale).

analyzer; the energy scale was adjusted in such a manner that channel zero corresponds to zero energy.

Accidental coincidences were not expected to have a noticeable influence on the shape of the observed summing distributions in view of the source strength used (of a few μC) and the resolving time ($2\tau = 30$ ns) of the available coincidence arrangement. This was verified by introducing a 60 ns delay into one of the channels.

3. Discussion

The summing cascades studied in this work may be classified into two fairly distinct groups, *viz.* one in which the two component energies are similar (^{60}Co , ^{46}Sc , ^{62}Zn) and another in which they differ by roughly a factor of two (^{88}Y , ^{22}Na , ^{75}Se). In the

summing spectra of the latter group the distribution shows two characteristic humps, corresponding to the photopeak positions of the two gamma rays in the single spectrum. Moreover for the case of ^{88}Y a summing distribution was constructed by adding, for every channel of the sum spectrum, the products of the intensities of the single gamma rays in such channels as could contribute to that particular channel of the summing distribution (fig. 2). It is seen that, qualitatively at least, the shape of this "semi-theoretical" summing distribution agrees with that of the experimental one. (The reliability of the lower channels of the pulse height analyzer being somewhat questionable, we replaced the contents of the channels below number 5 by an estimated extrapolation for the calculation of the "semi-theoretical" spectrum.)

In the summing spectra of the "similar" group evidently the two humps mentioned above cannot be observed separately and one can notice that the continuous distribution for this group is somewhat different from that of the "dissimilar" spectra. This can be easily seen in figs. 2 and 3, where the two typical examples of ^{88}Y ("dissimilar") and ^{60}Co ("similar") are represented. Fig. 3 also shows the shape of the summing distribution of ^{60}Co as observed in a measurement of the single gamma spectrum of this nuclide. This distribution appears to be well represented by the summing distribution measured by means of the method described in this paper, in the energy region where the comparison can be made. On the other hand the spectrum of a single gamma ray of energy comparable to the total energy in the summing distribution is very much different from the sum spectra that are observed experimentally (fig. 3).

For the peak at the high energy end, corresponding to the addition of two photopeak events, there is, however, no essential difference between the "similar" and the "dissimilar" cases. In fact, as shown in fig. 5, the ratios valley/peak and shoulder/peak seem to be dependent on the energy sum alone and not on the similarity or dissimilarity between the component gamma rays. The logarithms of both of these ratios appear to be fairly linear functions of the energy sum between 1800

2800 keV; a linear interpolation in this range of energy will therefore yield reasonably accurate estimates.

The spectra from the "similar" and the "dis-

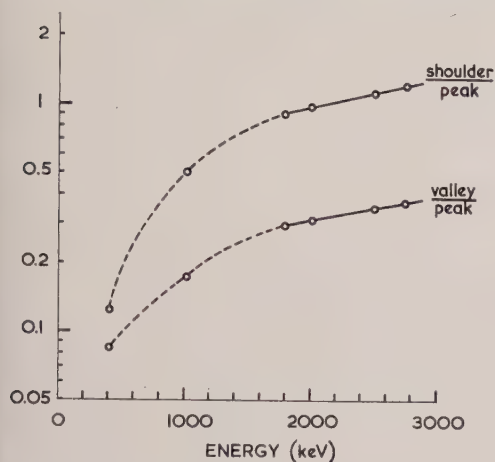


Fig. 5. Ratios shoulder/peak and valley/peak for the various summing distributions studied as a function of the cascade energy.

similar" group have been plotted together in Figs. 6 and 7 respectively. In these figures a double logarithmic scale has been used and the different spectra have been displaced so as to make the summing peaks coincide. Also the photopeak posi-

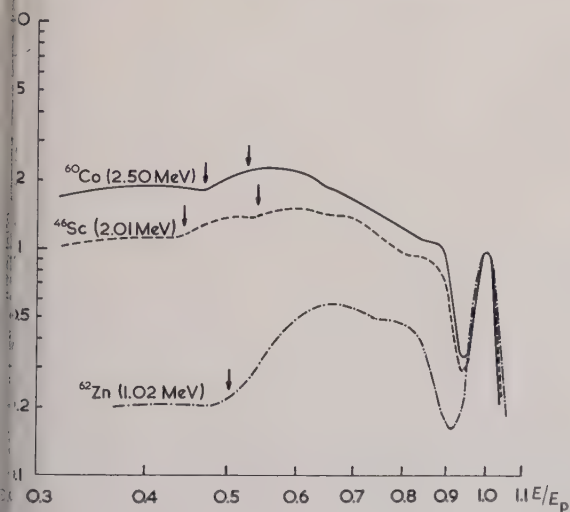


Fig. 6. Summing distributions for the cascades in the "similar" group. Energy and intensity of the summing peaks normalized to unity. (Arrows indicate the position of the component peaks in the direct spectrum; the curves are labelled by nuclide and cascade energy.)

tions of the single component gamma rays have been indicated for each of the spectra. We think it is possible to interpolate summing distributions for other cascades fairly reliably from these graphs, if the relation of the characteristic humps in the summing distribution to the photopeak positions of the component gamma rays in the single spectrum is observed.

We therefore have confidence that the method described above enables one to determine the shape of the summing distributions also in the energy region where it is obscured by the single gamma rays, and we think that this method offers interesting possibilities, *e.g.* for cases in which one wants to distinguish between the summing distribution and a possible weak cross-over transition, or for cases where other weak gamma rays of high energy may be concealed by the summing distribution from a cascade of high intensity.

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The authors would like to thank Prof. Dr. P. C. Gugelot, Prof. Dr. A. H. W. Aten Jr. and Prof. Dr. G. Cortini for their interest in this work.

They are indebted to Prof. Dr. A. H. Wapstra, Dr. R. van Lieshout and Dr. R. A. Ricci for valuable discussions and criticism. They would also like to

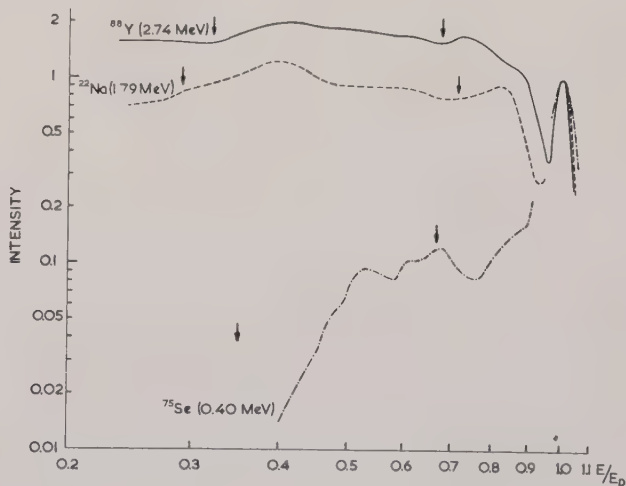


Fig. 7. Summing distributions for the cascades in the "dis-similar" group. Energy and intensity of the summing peaks normalized to unity. (Arrows indicate the position of the component peaks in the direct spectrum; the curves are labelled by nuclide and cascade energy.)

express their sincere gratitude and appreciation to Dr. G. J. Nijgh for his many valuable suggestions and for the willing sacrifice of his time and energy during the course of this work. Thanks are due to the personnel of the synchrocyclotron for the irradiations of the sources, and to the personnel of the chemistry department for the chemical separations.

This work forms part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (F.O.M.)" which is financially supported by

the "Nederlandse Organisatie voor Zuiver-Wetenschappelijk Onderzoek (Z.W.O.)".

Note added in proof: In a recent publication Johnson et al. (N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. **12** (1961) 1546) discuss a similar sum-coincidence circuit, used in the study of ^{134}I , where residual summing appreciably distorts the high energy region.

AN EXPERIMENTAL EQUIPMENT FOR THE RAPID RECOGNITION OF EXCURSIONS IN REACTORS AT LOW FLUX LEVELS

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Excursion detection equipment of a novel type described in a previous, mainly theoretical, paper has now been subjected to extensive experimental tests. These tests have confirmed that the equipment can give warning of the commencement of an excursion in a time little greater than the theoretically predicted absolute minimum time, over a wide range of conditions. The response of the equipment can be limited so that it does not

respond to longer periods, such as would be used to effect controlled increases in power level, at the expense of some loss of performance for periods just below the limit. The performance for really short periods remains unimpaired. The mathematical approach used in the design of this equipment may have applications to similar statistical problems in entirely different fields.

Introduction

In a paper¹⁾ published in 1960, the statistical problem of recognising as rapidly as possible a significant increase in the rate of arrival of pulses

purpose of the present paper is to describe the experimental results in more detail and to add some further theoretical results. The equipment described in the original paper¹⁾, consisted of a

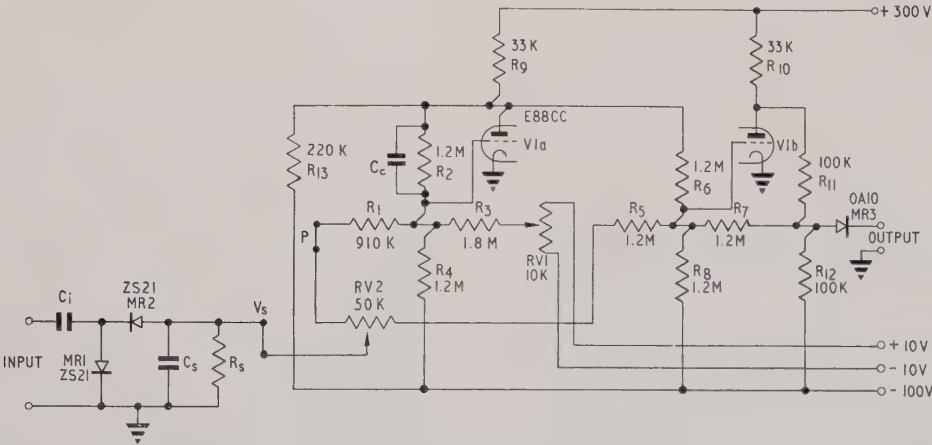


Fig. 1. A single diode pump and biasing circuit of the multiple pump unit.

occurring at random was analysed. Such recognition is of obvious importance for the early detection of an excursion in a reactor which is operating at a low power level, so that the neutron flux is measured by counting individual neutron pulses from a suitable detector. An electronic equipment designed to operate in little more than the theoretical minimum time was described and it was stated that the preliminary experimental results obtained with it were in accordance with the theory. The

sequence of diode pump circuits, each as shown at the lower left in fig. 1, with different time-constants $R_s C_s$ and with appropriate auxiliary circuits to give warning of a significant increase in the output voltage of any one of them. Significant is used here in the strict statistical sense of being extremely unlikely to occur due to the purely random fluctuations of the output voltage. Such fluctuations occur, at a steady mean rate of the input pulses,

¹⁾ C. H. Vincent, Nucl. Instr. and Meth. 9 (1960) 181.

due to the random timing of the pulses. The significance of any given voltage excursion is specified by a significance factor K , which is the voltage increase divided by the standard deviation of the voltage in the random fluctuations. The experimental results obtained fall naturally into three parts, response time measurements on a single circuit, response time measurements on a multiple circuit and false alarm rate measurements on a multiple circuit. This paper should be read in conjunction with¹).

2. Description of the Equipment

It was shown in¹) that an exponential excursion can be detected by a diode pump circuit in a time very close to the theoretical minimum time set by statistical considerations, over a wide range of conditions, provided that

1. The pulses are applied to a diode pump circuit having a timeconstant of a certain optimum value determined by the initial steady pulse rate before the excursion and by the period of the excursion.

2. An auxiliary circuit is provided which indicates when the output voltage has suddenly increased by more than K standard deviations of the output voltage, where K is a suitable constant, say 10. Excursions of exact exponential form were considered, to permit precise calculations and comparisons with experiments, but there is reason to believe that equally satisfactory results would be obtained with any other form of rising pulse rate, as is discussed further below and in Appendix 2 of this paper. The type of diode pump circuit used is quite standard, as shown in fig. 1. It should be preceded by a suitable flip-flop, which converts all the input pulses received to a standard amplitude and shape, with a known short dead-time. As the standard deviation of the output voltage fluctuations increases in proportion to the square root of the mean output voltage, as the input pulse rate is increased, it is difficult in practice to find a simple and accurate means of biasing a discriminator to trigger at a voltage level corresponding to a precisely constant significance factor. It was therefore suggested in¹) that a linear bias approximation should be used. With this, the bias consists of a fixed voltage plus another voltage proportional to

the output voltage. Such a bias can be made to approximate roughly to the required square root bias law over a range of 1:10 in the input pulse rate and gives a higher bias outside this range. Such a bias may be obtained by a second diode pump circuit of opposite polarity, with a suitable longer time-constant, the output of which is mixed with the output of the working diode pump circuit and with the fixed bias, as described in¹). Alternatively it may be obtained by a circuit of the type shown in fig. 1. In either case, the time-constant of the biasing circuit is large enough to ensure that no appreciable change in its output occurs during a fast excursion. On the other hand, this circuit follows slow controlled changes in the power level and adjusts the bias accordingly.

In fig. 1, the anode-follower VIa inverts the negative output of the diode pump circuit with a gain of 1.2, at the same time integrating it with a suitable time-constant determined by R_2 and a parallel capacitor C_c . The ratio R_2/R_1 allows for the finite loop gain of VIa. The output from VIa is mixed with the original diode pump output in the second anode-follower VIb, both being inverted. A zero adjustment for the output of VIa, controlling the fixed component of the final bias, is provided by the preset potentiometer RVI. The preset potentiometer RV2 is provided to allow compensation for tolerances in components and to ensure accuracy of the variable component of the bias. The output of VIb is connected to the discriminator input line by the diode MR3, so that the discriminator may be common to other similar circuits, if required. The discriminator is set to trigger when its input goes positive with respect to earth. The overall negative bias at the output of the biasing circuit corresponds to the voltage increment for $(0.2 \rho T = 62.5)$ pulses into the diode pump, where ρ is the initial mean rate and T is the time-constant $R_s C$ (with appropriate allowance for the resistances R_1 and R_5 , if R_s is high). It was shown in¹) that such a bias corresponds to a significance factor $K = 10$ in the middle of a suitable range, exceeding the value at either end, as shown in fig. 2. The continuous curve in this figure shows the exact bias required for a constant K of 10, while the dotted line shows the actual bias given by the linear approximation.

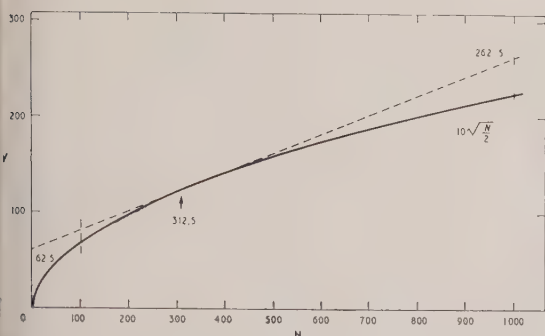


Fig. 2. The quantity N is the output voltage of the diode pump unit expressed as a multiple of the voltage increment per unit and is equal to ρT , apart from any saturation effect. The quantity ΔN is the corresponding bias.

approximation. 10 is an arbitrarily chosen but suitable value for K . The circuit of fig. 1 is carefully biased to minimise the effects of any sources of drift in the fixed component of the bias and all the supplies are stabilised, including the heater supply. A computer type twintriode, with good stability and balance between the two triodes, is desirable in this circuit. High stability resistors are used. The removable link at the point P is provided so that the circuit can be broken at this point and the resistor R_1 returned to earth. This enables the fast response of the circuit to be measured by means of a direct-current voltmeter at the junction of R_7 , R_{11} and R_{12} , when the input voltage at the point labelled V_s is changed by a known amount. This gives a gain of G_f , which is somewhat less than unity, owing to the finite open-loop gain of the amplifier V_{1b} and to the fact that a part of the potentiometer RV_2 is in series with R_5 . This potentiometer RV_2 should be adjusted until the overall direct-current gain G_t of the biasing circuit, with the link P in place, and the gain G_f are such that $G_t = -0.2 G_f$. This means that the overall gain of the feedback stage V_{1a} , multiplied by $1/R_6$, is precisely -1.2 . R'_5 is used here to denote the resistance of R_5 plus the resistance of the part of RV_2 between R_5 and the moving contact. The fixed component of the bias, controlled by RV_1 , should be set to equal $62.5 G_f V_i C_i / C_s$, where V_i is the input pulse voltage and C_i and C_s are the capacities indicated in fig. 1. This is also to be measured at the junction of R_7 , R_{11} and R_{12} , with no input to the diode pump.

3. Method of Measurement of Response Times

The apparatus which was used to measure the delay D in the action of the recognition circuit is shown in a block diagram in fig. 3. It includes a random pulse generator²⁾, which can give randomly timed pulses at a steady mean rate or can produce exponential excursions in the pulse rate on demand. The measurement of D itself is quite accurate and straight-forward, being done by counting regularly spaced pulses, at an accurately known frequency of 1 kc/s, from the time that the excursion is started to the time that the discriminator operates. The apparatus for this measurement is shown in the lower part of the figure. Highspeed relays are used, so that the contribution to the error from any difference in their operating times is negligible. The operating times are each less than 1 ms. To compare the value of D obtained with the theoretical value, it is necessary to know the time-constant T of the diode pump storage capacitor and leakage resistor, in the case of the single diode pump.

The initial steady pulse rate ρ and the excursion period P are also required, in both cases. The time-constant T may be obtained as the product of the resistance R_s (paralleled by R_1 and R_5 , see fig. 1) and the capacity C_s , which may be measured with

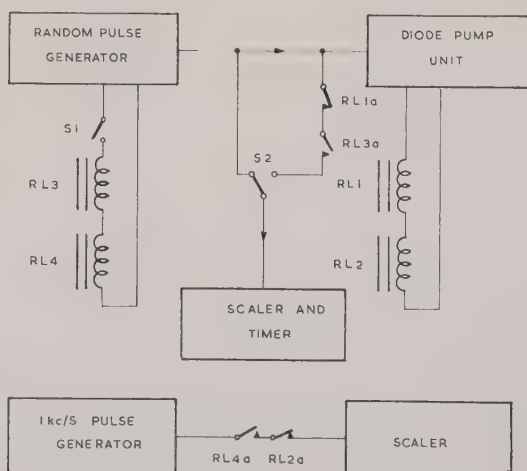


Fig. 3. Block diagram of the experimental arrangement for measuring response times. The switch S_1 starts each excursion, while S_2 selects the conditions for steady-state or excursion measurements.

²⁾ R. J. Lamden, Nucl. Instr. and Meth., **13** (1961) 247.

sufficient accuracy on a suitable bridge. The values of ρ and P are selected by the setting of the random pulse generator but, to minimise the effects of any drift in the calibrations for these, they may be measured anew at the time of each experiment, as follows. The value of ρ is determined by counting the output pulses, in the scaler and timer shown, for a sufficiently long and accurately known time interval just before the excursion starts. The value of P is determined from N_e , which is counted in the same scaler and is the number of pulses which have, at the time of detection, been sent out by the pulse generator during the excursion. The following relationship is used for this determination.

$$N_e = \int_0^D \rho e^{t/P} dt$$

(where t is the time)

$$= \rho P (e^{D/P} - 1)$$
$$\frac{N_e}{\rho D} = \frac{P}{D} (e^{D/P} - 1)$$
$$= \frac{1}{X} (e^X - 1) \text{ where } X = D/P .$$

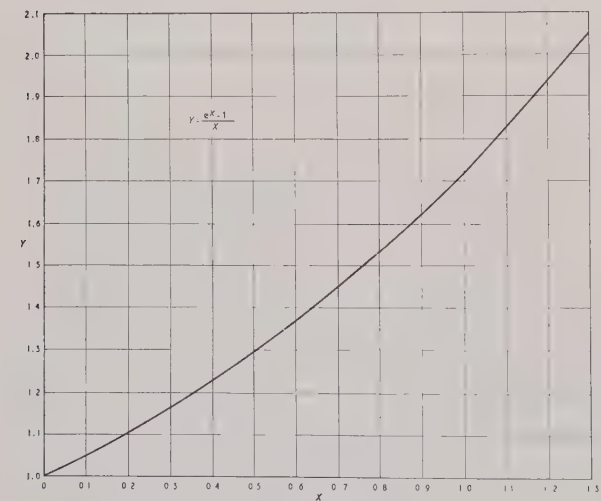


Fig. 4. The relationship used in determining the period P from the number of pulses N_e during the excursion. $Y = N_e/\rho D$ and $X = D/P$.

This function of X is plotted in fig. 4, which may be used conversely to find the value of X , and therefore of P , from the experimental value of the function.

4. Effects of Saturation and of Dead-Time

In¹⁾ the effect of saturation in the diode pump was not considered in any detail. It was estimated that, under suitable practical conditions, this effect would not be too serious. The effect has now been analysed in more detail and the validity of this conclusion has been confirmed. This analysis is given here in Appendix 1.

The experimental results reported here were all made with a small dead-time of $2.4 \mu s$ in the input pulse generating circuit and the deadtime has not exceeded 2.7% of the total time.

5. Response Time of a Single Circuit

Given a source of randomly timed pulses, capable of generating exponential excursions in the pulse rate, one may test the response time of the single diode pump circuit and biased discriminator for excursions of different initial mean rates and periods. The absolute time scale has no significance in the theory and the calculated results for a single circuit may be put in the general dimensionless form shown in fig. 5. In this figure, the ordinate

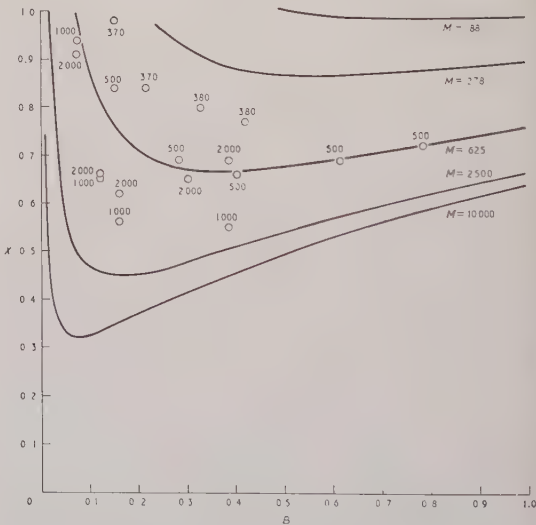


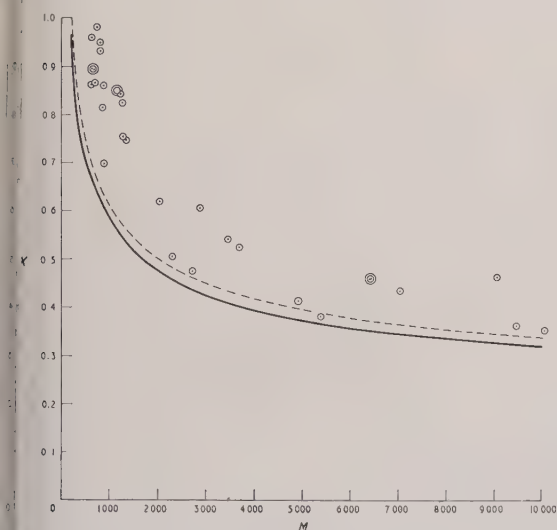
Fig. 5. Comparison of experimental and theoretical response times for the single diode pump circuit. The number against each experimental point is the value of M .

is the delay time D between the start of the excursion and the operation of the discriminator, divided by the period P of the excursion. B is the time constant T of the working diode pump circuit

ded by P . M is the initial steady pulse rate ρ , multiplied by P . The curves give the predicted results for the circuit described. A number of experimentally obtained points are also shown. It can be seen that, on the whole, these points are in reasonably good accordance with the theoretical curves.

Response Time of the Multiple Circuit

The period of any particular excursion requiring detection may lie within a wide range of values and



6. Comparison of experimental and theoretical response times for the multiple diode pump circuit.

not, of course, be known in advance. In¹), it is suggested that the problem of matching the time-constant of the diode pump circuit to the optimum value (as shown in fig. 5) for the period of any excursion which comes, should be met by using a multiplicity of diode pump circuits, with closely spaced time-constants, and taking the response of the first one to reach the discriminator operating level. Provided that a sufficiently close spacing of time-constants is used, one circuit must always be close to the optimum condition. Assuming such close spacing, one can plot the optimum value of X as a function of M , as shown by the full line curve in fig. 6. This curve was actually computed numerically, but five points on it could, of course, be obtained from the minima of the five curves in fig. 5. In practice, the total number of diode pumps in a

multiple circuit must be kept to a reasonable number, and an arbitrary factor of $\sqrt{10}$ was chosen for the spacing of the time-constants. It is possible to calculate the upper limit of the increase in X at this spacing, due to the fact that the timeconstant of the first circuit to respond may not be precisely at the optimum, and this limit is also shown in fig. 6 by the dotted curve, which lies closely above the full line one. It was shown in ref.¹) that the full line curve in fig. 6 lies closely above a similar curve giving the results for a diode pump circuit exactly biased for the same value of K and that this in turn lies closely above an absolute optimum curve for that value of K , (10). It follows, therefore, that even the dotted curve is not far above the absolute optimum.

In the multiple diode pump unit, the output from the first diode pump circuit to pass its own bias level is used to operate the discriminator. The individual diode pump circuits and their biasing circuits are as shown in fig. 1. The outputs are connected, through a diode in each case, to a common line to the discriminator. The first output to go positive causes its diode to conduct and operate the discriminator, the other diodes remaining cut off. Fig. 6 shows a considerable number of experimental points, obtained in this way. It will be seen that these are in good general agreement with the theoretical curves, although somewhat higher, on the whole. The performance is nevertheless very satisfactory from the point of view of possible applications to an automatic protection and warning system.

7. False Alarm Rate Tests

If an equipment such as that described is to be used in practice to give warning of reactor excursions, it must be free from false alarms. Such false alarms can arise from two distinct sources. Firstly, there are false alarms arising from an inadequate statistical margin against the expected random fluctuations. Alarms from this source should be negligible, according to the theory, if the parameters of the equipment are correctly set and do not drift. Secondly, there are spurious fluctuations such as those due to mains-borne interference and faulty components. Such fluctuations must be

rigorously eliminated by the usual methods. Experimental tests on freedom from false alarms were carried out on the multiple diode pump unit, as this was more likely to show a false alarm than the single diode pump circuit and also it corresponded more closely to the type of protection equipment which might finally be used in practice. The single diode pump circuit was tested incidentally, to some extent, when its response time was being measured, in that it was found to be free of false alarms between the excursions applied.

The probability per century of a false alarm from the multiple pump unit, as designed, is theoretically very small indeed and it is obviously impracticable to measure the actual rate to confirm that this is achieved. The equipment has been left set up for periods of several days in its normal condition without any false alarms occurring. Suitable pulse rates were obtained from a radioactive source and detector in these tests. The probability that a given diode pump circuit will have an output at any instant above a given bias voltage decreases very rapidly as the bias voltage is increased (see ref.¹), and the number of false alarms obtained may be expected to decrease accordingly. It is therefore of considerable interest to set the equipment up for false alarm tests with both the fixed and variable bias set at some chosen fraction of the normal value. In this way, tests were carried out with linear bias approximations to $K = 6.0, 6.5, 7.0, 7.5, 8.0$ and 9.0 , as well as 10 . When the logarithm of the reciprocal false alarm rate was plotted against the value of K , a rapidly rising characteristic was obtained (see fig. 7). This was extrapolated linearly by a least squares fit, as the accuracy of the successive settings of K was not very high, and it gave a false alarm rate of about one per 300 years at $K = 10$.

In the theory given in¹), it is assumed that the output voltage must exceed the discriminator bias level for a minimum time τ before the discriminator triggers. It follows from this that the false alarm rate ρ_F is given by

$$\rho_F = \frac{\theta P(K)}{\tau}$$

where $\theta < 1$ and $P(K)$ is the probability in a Gaussian distribution of exceeding K standard

deviations. Now for reasonably large values of K say $K \geq 6$, it is a good approximation (to about 1 part in K^2) to take

$$P(K) = \frac{1}{\sqrt{2\pi}} \frac{e^{-\frac{1}{2}K^2}}{K}$$

giving

$$\log_e (1/\rho_F) = \frac{1}{2}K^2 + \log_e K - \log_e \theta + \log_e \tau + \log_e \sqrt{2\pi}$$

It is reasonable to suppose that the term $\frac{1}{2}K^2$ will predominate in any changes in $\log_e (1/\rho_F)$ with K . In fact, the experimental results given in fig. 7

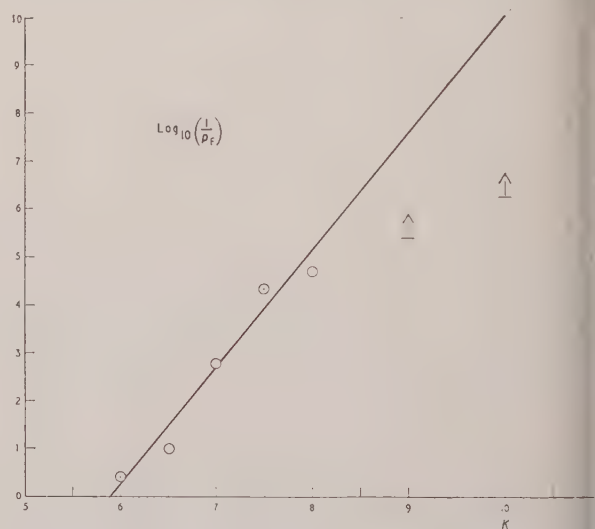


Fig. 7. Experimental plot of false alarm rate ρ_F against bias setting K . (The arrows indicate limits only.)

are roughly in accordance with this, as the slope of the line drawn through the points is of the right order (5.6 as compared with a predicted value of 7.14 at $K = 7$, taking the $\log K$ term into account). Since the K^2 term has an increasing rate of rise as K increases, the linear extrapolation used in fig. 7 in estimating the mean time between false alarms at $K = 10$ is probably conservative, in theory.

The multiple circuit was also tried at its normal bias setting for $K = 10$ with the A.W.R.J. research reactor Horace, with promising results.

8. Provision for Controlled Increases in Power

The primary requirement in the performance specified for the present equipment was that it should detect the commencement of an excursion, particularly a short-period excursion, with the utmost possible speed. An essential corollary of the

that it should be sufficiently free from false alarms when the reactor power level and the input pulse rate are constant. It has been confirmed both theoretically and experimentally that both these requirements can be met. A rather practical requirement for use on an actual reactor is that it should be possible to make controlled increases in the reactor power level, with a specified minimum period, without setting off the alarm. If equipment is installed in a reactor for detection purposes, it is obviously undesirable that it should have to be put out of action during a controlled power increase, in order to permit that increase without alarm operation.

An ideal solution, at least in theory, would be to withdraw the neutron detector from its initial position to a position of lower neutron flux in a controlled manner during the power increase, so that the mean input pulse rate would remain constant, in spite of the power increase. A simpler method in practice is to reduce the response of the excursion detection equipment to long-period excursions with more than the specified minimum period. This may be done by a suitable choice of the circuit time-constant and of the maximum diode pump time-constant. For example, if these are both 3 s, it will be found that reactor power increases of more than 10 s period (7 s doubling time) will not set the alarm off. With excursions of periods 4 s or less, the alarm operates rapidly. The speed is not quite as high in this region as would be calculated from the results previously given, owing to the proximity of the limiting period. However the speed is still quite adequate for the purpose, especially as such periods still allow adequate time for other protective action. The main danger which this equipment is designed to guard against is the possibility, however remote, of a fractional second period being set up by some accident. For such periods, the alarm operation is still very prompt indeed and in close accordance with the figures given above.

Responses to Excursions of Different Forms

It has been stated¹⁾ that the diode pump circuit described should respond well to any form of rising waveform in the excursion. This statement was

made on the grounds that the response depends upon a certain type of fit between the function $f(t)$ specifying the form of the excursion and the function $w'(t')$ specifying the voltage waveform during discharge of the diode pump storage condenser. The pulse rate $\rho(t)$ during the excursion (that is, for $t > 0$) is defined by

$$\rho(t) = \rho [1 + f(t)]$$

while for the diode pump circuit $w'(t')$ is given by

$$w'(t') = e^{-t'/T}$$

where t' is the time from the arrival of a pulse and T is the time-constant of the storage condenser and its leakage resistor. The nature of the fit required is that $w'(D - t)$ should be as closely as possible proportional to $f(t)$, where D is the time from the start of the excursion to its detection, as previously defined. Since the fit does not have to be a very precise one¹⁾, a wide variety of rising waveforms may be dealt with efficiently by making a suitable choice of T in each case. This choice of T is, of course, made automatically, in the normal use of the equipment, since the response of the fastest circuit is taken.

The case of an exponentially rising waveform has already been investigated both theoretically and experimentally. This case corresponds to a step increase in reactivity in a critical assembly and approximates to a linear rise, at first. Other conditions of possible interest are a step increase in the rate of change of reactivity and a step increase in the second derivative of the reactivity. These correspond to imparting an outward velocity and an outward acceleration, respectively, to a control rod. The corresponding waveforms in the pulse rate approximate at first to a parabola (square law) and a cubic, respectively. It is therefore an interesting test of the general applicability of the diode pump circuit to examine its response to excursions with the rate rising in proportion to the elapsed time, to its square and to its cube. It is possible to show (see Appendix 2) that the optimum condition in each case is such that T/D has the value 0.465, 0.323 or 0.246 respectively, (see fig. 13). It is also possible to show that for a diode pump circuit with exact

biasing the corresponding increases in D due to the departure from the absolute optimum conditions involved in the use of the diode pump circuit are only of the order of 1%, 0.23% and 0.082%. These increases are all quite negligible from the point of view of practical application of the circuit as an excursion detector and confirm that its good response does not depend on a close adherence to the exponential form of excursion always considered in previous calculations.

10. Further Consideration of Extreme Conditions

In¹⁾, the conditions mainly considered were those in which $200 < M < 10000$, although certain minimum performances were also found for greater and lesser values of M . The results under extreme conditions are given further consideration below.

10.1 THE RELATIONSHIP BETWEEN THE ABSOLUTE OPTIMUM CASE AND THE DIODE PUMP CIRCUIT WITH EXACT BIAS

For large values of M , the value of X becomes small and the pulse rate in the relevant part of an exponential approximates to a linear function of time. The value of X for the diode pump case with exact bias therefore tends to a limiting ratio of about 1.01 to the absolute optimum value, as M is increased, as shown in Appendix 2. For small values of M , the quantity X becomes relatively large and, in the limit, it may be said that a diode pump circuit with a time-constant T such that $T = P$ provides a perfectly fitting weighting function for an exponential excursion of period P . It follows that, in the limit, X is the same for the diode pump case with exact bias as for the absolute optimum case. For intermediate values of M , the degrees of fitting between the curves concerned, and therefore the increases in X , are also intermediate. To summarize, we may say that the value of X for the diode pump case with exact bias is identical with the absolute optimum value for low M and increases relatively until it is 1% higher at high M .

10.2. CONSIDERATIONS IN THE LOW M REGION

The theoretical curves for the diode pump circuit with the linear bias approximation can easily be

extended down to any value of M required and this is also true of the exact bias and absolute optimum curves, which become effectively identical with each other in this region. As has already been pointed out¹⁾, the linear bias approximation in this region gives a result approximating to the detection of the first 63 pulses in the excursion. The corresponding curve becomes asymptotic here to $X = \log_e (62.5/M)$ (see Appendix 3). This is shown in fig. 8, in which M is plotted on a logarithmic

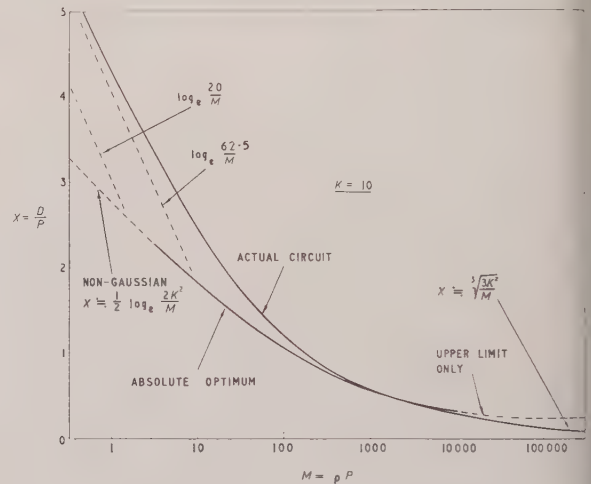


Fig. 8. Extended plot of X against M .

scale, to facilitate showing a wider range of values. This performance as $M \rightarrow 0$ will be achieved, for example, by a circuit in which

$$T \equiv BP = \frac{P\sqrt{62.5}}{\sqrt{M}},$$

so that

$$N = \rho T = \frac{\rho P\sqrt{62.5}}{\sqrt{M}} = \frac{M\sqrt{62.5}}{\sqrt{M}} = \sqrt{62.5M}.$$

As given in¹⁾, the quantity N is the mean steady voltage in the storage condenser, expressed in terms of pulse increments, and equals ρT . Now it is clear that as $N \rightarrow 0$ (since $M \rightarrow 0$) the probability of finding a voltage in the storage condenser equivalent to 62.5 pulse increments becomes less and therefore the actual circuit with its minimum bias of 62.5 pulse increments is not liable to suffer false alarms.

The absolute optimum curve for $K = 10$ is also shown extended into the region of low M in this

ture, and begins to deviate appreciably from the linear bias approximation curve. However, in this region, the number of pulses involved in the calculated optimum conditions is small and the statistics are no longer Gaussian, so that a deviation of $K (= 10)$ standard deviations is no longer an extremely improbable event. Taking an extreme case to illustrate this point most clearly, consider $\mu = 0.005$. (This represents an initial mean steady pulse rate of one pulse per 200 periods of the excursions.) In this region, the bias required approximates $K \sqrt{M/2}$ pulse increments (see Appendix 3) and for $K = 10$ this is $10 \sqrt{0.005/2} = 0.5$. Under these conditions, every pulse arriving would trigger the discriminator. It is therefore clear that the minimum bias voltage of a fixed number of pulse increments provided by the linear bias approximation system is not merely an incidental feature of a practical system but is also a theoretical necessity. For the actual circuit taken, this minimum number is 52.5. While this number is quite arbitrary and it is possible that a somewhat lower number could be readily chosen here, if desired, it is clear from fig. 8 that no major improvement in performance could be made in this way. The line which would be asymptotic to the curve with this number equal to 52.5, as well as the asymptote to the actual curve for $K = 10$ are shown (dotted) in fig. 8, to illustrate this.

10.3. RELATIONSHIP TO THE POISSON DISTRIBUTION

The statistics of the situation for low values of M may be considered in a simpler manner if one takes a different form of weighting function instead of the weighting function

$$w'(t') = e^{-t'/T}$$

which is appropriate for the diode pump circuit. This weighting function, which was referred to in ref.¹), but shown not to be optimum, is of the form

$$w'(t') = 1 \quad \text{for } 0 < t' < T$$

$$w'(t') = 0 \quad \text{for } t' < 0 \quad \text{and} \quad t' > T.$$

This weighting function would be appropriate to a sequence of scalars or registers, each counting the number of pulses in a time interval T , with different starting times. The distribution of the number of pulses recorded in any such interval T is a Poisson one and it is therefore of considerable interest to study how the probability of a positive deviation exceeding K standard deviations varies with the mean or expected number μ in a Poisson distribution. (μ corresponds to N in our application.) This probability must approach the value for a Gaussian distribution as the limit for large numbers. Fig. 9 shows this variation for $K = 10$, the logarithm of the reciprocal of the probability

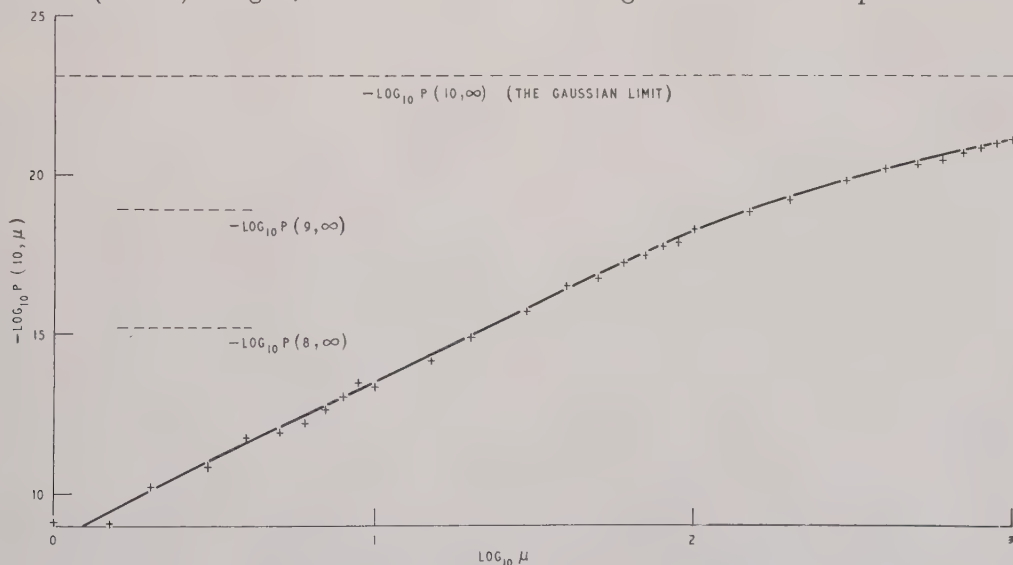


Fig. 9. The probability $P(10, \mu)$ of a positive deviation exceeding 10 standard deviations in a Poisson distribution of mean μ , plotted logarithmically as a function of μ . Only selected points have been calculated and the curve has been drawn by hand through them.

being plotted against the logarithm of μ . The Gaussian limit ($\mu = \infty$) for $K = 10$ is also shown, together with the same limit for $K = 9$ and $K = 8$. This enables the increase in the probability due to the finite value of μ to be considered in terms of the equivalent reduction on K . It is clear from this figure that it is desirable that at least some hundreds of pulses should be involved, if the equivalent reduction in K is not to be excessive. At $\mu = 400$, for example (corresponding to a standard deviation of 20 and a bias of 200) the equivalent reduced value of K is about 9.3. The circumstances in the actual circuit are more complicated, and on the whole more favourable, since any voltage present is composed of small residual contributions from previous pulses (which have decreased in accordance with the $e^{-t/T}$ law) as well as those from recent pulses, so that 62.5 pulse increments represents a larger number of actual pulses, with correspondingly better statistics. Nevertheless, the number 62.5 does not seem excessively large when viewed with respect to the above, and is probably of the right order, especially as no great gain in performance would be obtained by decreasing it, as seen earlier.

10.4. CONSIDERATION OF THE HIGH M REGION

In this region, the absolute optimum curve applies without qualification. The diode pump with exact bias curve is only 1% higher here and as the two curves are virtually indistinguishable over the whole range of fig. 8, with the scale used, it is not drawn separately. The theoretical curve for the diode pump case with the linear bias approximation could, of course, be extended into this region, as far as desired. However, this would only be justified with a circuit which was free from saturation effect. In Appendix 1 of the present paper, it is shown that the saturation effect is not serious for the actual circuit used for M up to 10000, at which value $X = 0.32$, theoretically. X cannot be more than this for higher values of M and if one considers only circuits in which the value of $N(= \rho T)$ is the same as at this point, that is, 745, ignoring other circuits which may have a faster response, although more saturated, one finds (from fig. 11, which is taken from ref.¹) that X must decrease to

0.25 or less. This is roughly indicated by the dotted extension of the linear bias approximation curve on the right-hand side of fig. 8. This dotted extension is only an upper limit for the actual circuit used, owing to the difficulty of making precise allowance for the effect of saturation, and even the true curve for the actual circuit would not be in any way absolute. The optimum curve could be approached as closely as desired in this region, provided that steps were taken to overcome saturation and the increase of K which occurs at high N with the simple linear bias approximation. It is possible to reduce the saturation effect by the use of a more complicated diode pump circuit. The increase in K could be overcome by the use of a non-linear biasing circuit or by the use of multiple circuits with more than one type of linear bias approximation, so that the square root law of fig. 2 was effectively defined by more than one of its tangents. However, it is unlikely that these improvements would be necessary or would justify the extra complication needed, in practice. In any case, this equipment is mainly designed to effect improvements in performance in the region of statistical difficulty, at low M , rather than in the region of high M , where the statistical difficulties eventually disappear, at high enough values.

11. Comparison with Standard Reactor Protection Equipment

A spare Logarithmic Ratemeter and Period Meter type 613 (A.E.R.E. type 1508) from one of the establishment reactors was set to trip at 7% period (5 s doubling time). It was then set up with the multiple diode pump excursion detector equipment and subjected to the same excursions as the latter, by means of the random pulse generator. The excursion detector on this occasion had a counterbalancing time-constant of 1 s and a maximum diode pump time-constant of 1 s, so that it was set to be insensitive to excursions of more than about 3 s period and was therefore considerably more heavily restricted in this respect than the standard unit. The results are shown in fig. 10 which is in the same form as fig. 8. The points for the excursion detector all lie close to the same mean curve, which is shown dotted. The points for

period meter are widely spread and dependent on the period. Freehand curves have been drawn through each set of points to identify the period concerned. The contrast in performance is marked,

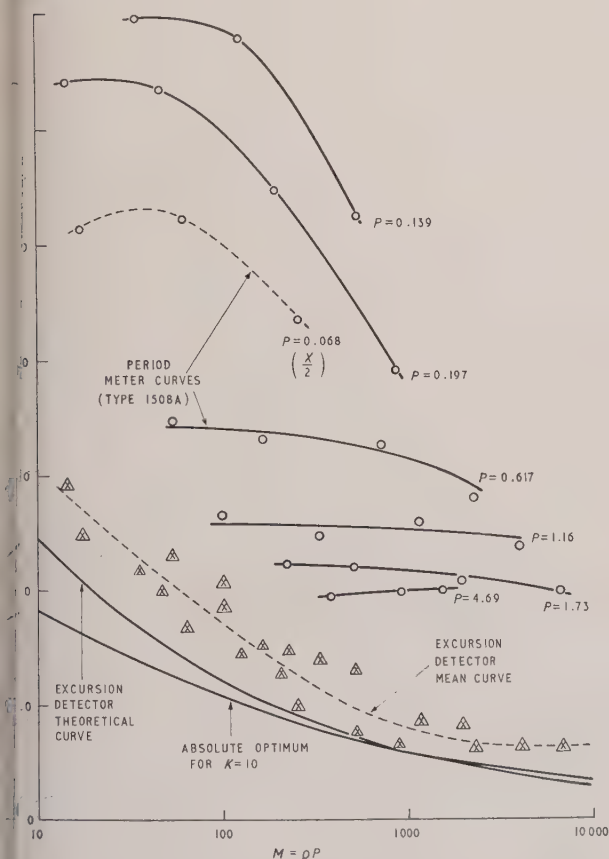


Fig. 10. Comparison of the performance of the excursion detector with that of a standard reactor period meter trip circuit (A.E.R.E. type 1508A) for the same excursions. The period P is given in seconds.

especially for short periods and especially considering that the excursion detector was set up to trip only for appreciably shorter periods than the period of the standard unit.

2. Possible Applications to Slower Phenomena

While the method described has been developed with particular reference to the problem of rapid detection of excursions in reactors, the statistical theory given in ref.¹) applies quite generally, whenever it is desired to recognise rapidly a significant increase from a steady value in the

probability of discrete events of a specified type occurring with random timing. The actual time-scale is irrelevant and might be much slower. For example, the theory could be applied to the continuous monitoring of a channel containing a slightly radioactive fluid, when the earliest possible warning of a significant increase in the count rate is desired. Other possible applications may exist right outside the radioactivity field, as in biology or medicine. Equipment of the type described in this paper might be used as an analogue computer for the necessary calculations, in such cases, if the events concerned were recorded on magnetic tape as pulses, on a suitable time-scale, and then read into the equipment at high speed. The magnetic tape would then be used, in effect, as a flexible means of adjusting the time-scale of the phenomena to suit that of the equipment. The reading of the tape could be repeated at sufficiently frequent intervals for the delay of one interval between successive readings to be relatively unimportant, on the slow timescale concerned. The theory could no doubt be applied conveniently by means of other computing methods also.

13. Conclusions

It has been confirmed that it is possible to detect excursions in the mean rate of pulses occurring at random in a time that is not much greater than the theoretical minimum time, as was predicted in ref.¹). The equipment used was in accordance with the principles given in that paper. The equipment has been made in the form of a multiple diode pump unit which approximates to an actual warning device which might be used on a reactor and it has, in fact, been tested on a research reactor. It has also been extensively tested with a random pulse generator simulating a reactor. The results confirm that both the rapidity of response and the freedom from spurious alarms are in accordance with the theory, which predicts that the false alarm rate should be negligible, with the biasing conditions used. Care is needed to achieve the necessary stability and freedom from interference, but these requirements may be met by the use of standard techniques.

Appendix 1

THE EFFECT OF SATURATION ON A DIODE PUMP EXCURSION-DETECTION CIRCUIT

This appendix should be read in conjunction with ref.¹). We define N as

$$\frac{V_s}{V_i} \frac{C_s}{C_i},$$

where V_i is the pulse input voltage, V_s is the storage condenser output voltage, and C_i and C_s are the two capacities, as shown in fig. 1. In the absence of saturation, $N = \rho T$ (where $T = R_s C_s$) and the voltage excursions on the storage condenser have the form shown in fig. 11 (from ref.¹). Allowing for saturation, we have in the steady state

$$\rho(V_i - V_s)C_i = \frac{V_s}{R_s} \quad (1)$$

$$\rho T \left(\frac{C_i}{C_s} \right) \left(1 - \frac{V_s}{V_i} \right) = \frac{V_s}{V_i} \quad (2)$$

$$\frac{V_s}{V_i} = \frac{\rho T (C_i/C_s)}{1 + \rho T (C_i/C_s)}$$

$$N = \frac{\rho T}{1 + \rho T (C_i/C_s)}. \quad (3)$$

If the increase in the output voltage necessary to overcome the discriminator bias is set to be given by

$$\Delta N = \alpha + \beta N \quad (4)$$

this gives

$$\Delta N = \frac{\beta \rho T}{1 + \rho T (C_i/C_s)} + \alpha$$

$$N + \Delta N = \frac{(1 + \beta) \rho T}{1 + \rho T (C_i/C_s)} + \alpha. \quad (5)$$

It follows that the final and minimum value of the saturation factor $(1 - V_s/V_i)$ during the excursion up to the time of detection is given by

$$1 - (N + \Delta N) \left(\frac{C_i}{C_s} \right) = 1 - \frac{(1 + \beta) \rho T (C_i/C_s)}{1 + \rho T (C_i/C_s)} - \alpha \left(\frac{C_i}{C_s} \right)$$

$$= \frac{1 - \beta \rho T (C_i/C_s) - \alpha (C_i/C_s) \{ 1 + \rho T (C_i/C_s) \}}{1 + \rho T (C_i/C_s)} \quad (6)$$

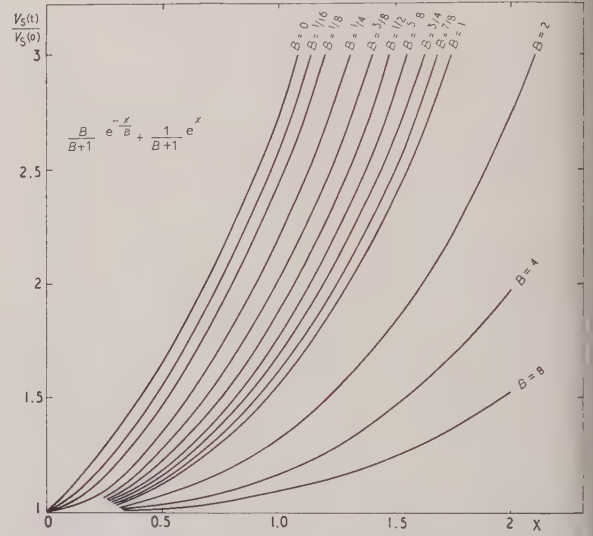


Fig. 11. The response of an ordinary diode pump circuit to an excursion. ($B = T/P$.)

as compared with the initial value of this factor, which is

$$\frac{1}{1 + \rho T (C_i/C_s)}.$$

Let us now compare the response of this circuit with the response of a saturation-free circuit ($C_s \gg C_i$) to the same excursion, when the latter circuit has parameters V_i' , C_i' and C_s' (V_i' is very large) such that the voltage increment per pulse

$$\frac{V_i' C_i'}{C_s'} = \frac{V_i C_i}{C_s} \frac{1}{1 + \rho T (C_i/C_s)} \quad (7)$$

and has

$$\alpha' = \alpha \{ 1 + \rho T (C_i/C_s) \} \quad (8)$$

and also has $T' = T$ and $\beta' = \beta$. The steady initial voltage on the storage condenser (from eq. (2)) and the bias in volts are then the same for the two

circuits and the initial voltage increment per pulse the same. The voltage increment per pulse in the actual circuit falls off during the excursion by a factor having a minimum value (at the time of detection) of

$$1 - \beta \rho T (C_i/C_s) - \alpha (C_i/C_s) \{ 1 + \rho T (C_i/C_s) \}.$$

Let us now modify the excursion applied to the saturation-free circuit by giving it a period of $(1 - \theta)$, instead of P , where

$$D/P = 1 - \beta \rho T (C_i/C_s) - \alpha (C_i/C_s) \{ 1 + \rho T (C_i/C_s) \} \quad (9)$$

is the time from the start of the excursion until detection).

This makes its input current at any instant during the excursion

$$\rho V_i C_i' e^{(1-\theta)t/P} = \rho V_i C_i' e^{t/P} e^{-\theta t/P} \quad (10)$$

compared with the input current of the actual circuit, which is

$$\rho V_i C_i e^{t/P} \left(1 - \frac{V_s}{V_i} \right) = \frac{\rho V_i C_i e^{t/P} (1 - f)}{1 + \rho T (C_i/C_s)} \text{ say } (11)$$

where $1 - f = e^{-\theta t/P}$ at $t = 0$, when both are 1, and at $t = D$, when both equal the expression given above in eq. (9). It is convenient to take $C_i = C_s$ (implying that C_i' is very small) to facilitate comparison between the circuits. We then have from eqs. (7) and (11) that the input current to the actual circuit is

$$\rho V_i C_i e^{t/P} \left(1 - \frac{V_s}{V_i} \right) = \rho V_i C_i' e^{t/P} (1 - f). \quad (12)$$

Whereas $e^{-\theta t/P}$ has a decreasing rate of fall, V_s/V_i is a non-linear function of t following closely the general line of the appropriate voltage increase curve shown in fig. 11, to a suitable scale. To determine the first-order perturbation effect of saturation on the response, we shall assume, therefore, as is legitimate for this purpose, that this function has an increasing rate of rise throughout, so do all the curves in fig. 11, giving an increasing rate of fall to $1 - f$. It follows, then, from the manner in which we have defined θ , that $1 - f$ must be greater than $e^{-\theta t/P}$ at all intermediate

values of t between 0 and D (see fig. 12). The other factors on the right-hand sides of eqs. (10) and (12) are identical. The two circuits now have the same bias conditions and the same initial and final input

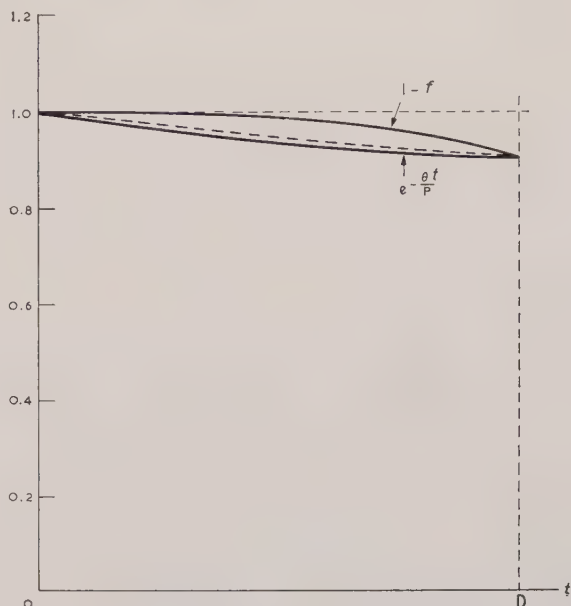


Fig. 12. The relationship between $1 - f$ and $e^{-\theta t/P}$.

currents, but the intermediate input currents of the actual circuit are greater. It therefore triggers first. That is to say, it triggers faster than a saturation-free circuit with the same value of T which is subject to the following conditions:

(a) The total bias is increased in the ratio

$$\frac{\beta \rho T + \alpha + \alpha \rho T (C_i/C_s)}{\beta \rho T + \alpha}.$$

(b) The period of the excursion applied is increased in the ratio $1/(1 - \theta)$.

Each of these changes has a less than proportionate effect on D' . This follows for (a), since the voltage against time curve for V_s in the excursion is concave upwards, in accordance with the curves of fig. 11, which are exact for a saturation-free circuit. It follows for (b) since the value of $B (= T/P)$ is decreased when the period is increased. The curve of fig. 11 that is followed is therefore a more steeply rising one. Consequently, the increase in D' is less than in proportion to the increase in P . It follows

that D' for the saturation-free circuit is increased altogether by less than the factor

$$\frac{\beta\rho T + \alpha + \alpha\rho T(C_i/C_s)}{(\beta\rho T + \alpha)(1 - \theta)}.$$

D for the actual circuit is less still. It therefore follows *a fortiori* that D and X for the actual circuit are increased by the saturation effect by less than the above factor. For small values of the increase, the result may be approximated to be saying that D is increased by less than

$$D \frac{\alpha\rho T(C_i/C_s)}{\beta\rho T + \alpha} + P \left[\beta\rho T \left(\frac{C_i}{C_s} \right) + \alpha \left(\frac{C_i}{C_s} \right) \left\{ 1 + \rho T \left(\frac{C_i}{C_s} \right) \right\} \right].$$

To consider a numerical example, take $\alpha = 62.5$, $\beta = 0.2$, $C_s/C_i = 10000$ and $\rho T = 750$. It is reasonable to assume that this example is fairly accurately treated by the first-order perturbation theory, which gives an increase in D of

$$D \frac{4.69}{212.5} + P(0.015 + 0.00625 \times 1.075) = 0.0221D + 0.0217P.$$

The effect of saturation is to produce an increase in D and X which becomes more serious with large values of ρT . It is shown in ref.¹) that a satisfactory performance can be obtained using only circuits in which T is small enough to make $\rho T < 750$. It

follows that the worst increase in the recognition time due to saturation with a suitable ratio C_i/C_s of 10^{-4} is given by the result of the above example. Since D is about $0.32P$ at the optimum for this value of ρT , the worst increase in X is given by

$$0.0221 \times 0.32 + 0.0217 = 0.029$$

which is not too serious.

We have assumed in the above discussion that values of α and β are chosen which would be suitable in the absence of saturation, and we have shown that in this case the increase in the response time due to saturation will not be too serious. Now in this case the bias used is at all times greater than $K\sqrt{N/2}$, where K is the chosen minimum significance factor. Moreover

$$K\sqrt{\frac{1}{2}N} = K\sqrt{\frac{1}{2}\rho T} \{1 + \rho T(C_i/C_s)\}^{-\frac{1}{2}}.$$

Now at any steady input pulse rate ρ the standard deviation of the output voltage, allowing for the decreased amplitude of the individual voltage increments due to saturation, is equivalent to

$$\sqrt{\frac{1}{2}\rho T} \{1 + \rho T(C_i/C_s)\}^{-1}$$

times the full voltage increment per pulse in the absence of saturation. It follows that the actual significance factor used is then greater than

$$K \{1 + \rho T(C_i/C_s)\}^{\frac{1}{2}}.$$

That is to say, the effect of saturation is to increase the significance factor for any given α and β . The probability of a false alarm is therefore decreased by the saturation.

Appendix 2

THE PERFORMANCE OF THE DIODE PUMP CIRCUIT FOR EXCURSIONS OF VARIOUS FORMS

Equation (1) of ref.¹) may be rearranged as

$$\frac{r^2}{\rho} = \frac{\left[\int_0^D w'(D-t)f(t) dt \right]^2}{\int_0^\infty \{w'(t')\}^2 dt'} \quad (1)$$

where r is the significance ratio of the excursion. For the diode pump circuit, this is

$$\frac{r^2}{\rho} = \frac{\left[\int_0^D e^{-(D-t)/T} f(t) dt \right]^2}{\int_0^\infty e^{-2t'/T} dt'} \quad (2)$$

Take $f(t) = (t/R)^3$, as an example. Then

$$\frac{r^2}{\rho} = \frac{2T^7}{R^6} e^{-2D/T} \left[\int_0^{D/T} e^y y^3 dy \right]^2 \quad (3)$$

where $y = t/T$. Integrating and rearranging this

$$\begin{aligned} &= \frac{2(3!)^2 D^7}{R^6} \left(\frac{D}{T} \right)^{-7} \left[e^{-D/T} - \left(1 - \frac{D}{T} \right) \right. \\ &\quad \left. + \frac{1}{2!} \frac{D^2}{T^2} - \frac{1}{3!} \frac{D^3}{T^3} \right]^2. \quad (4) \end{aligned}$$

Similar results are obtained for the other two cases $f(t) = t/P$ and $f(t) = (t/Q)^2$ with

$$\frac{2(1!)^2 D^3}{P^2} \left(\frac{D}{T} \right)^{-3}$$

$$\frac{2(2!)^2 D^5}{Q^4} \left(\frac{D}{T} \right)^{-5}$$

respectively replacing

$$\frac{2(3!)^2 D^7}{R^6} \left(\frac{D}{T} \right)^{-7}$$

and with the number of terms in the series on the right such that the highest power of D/T is the

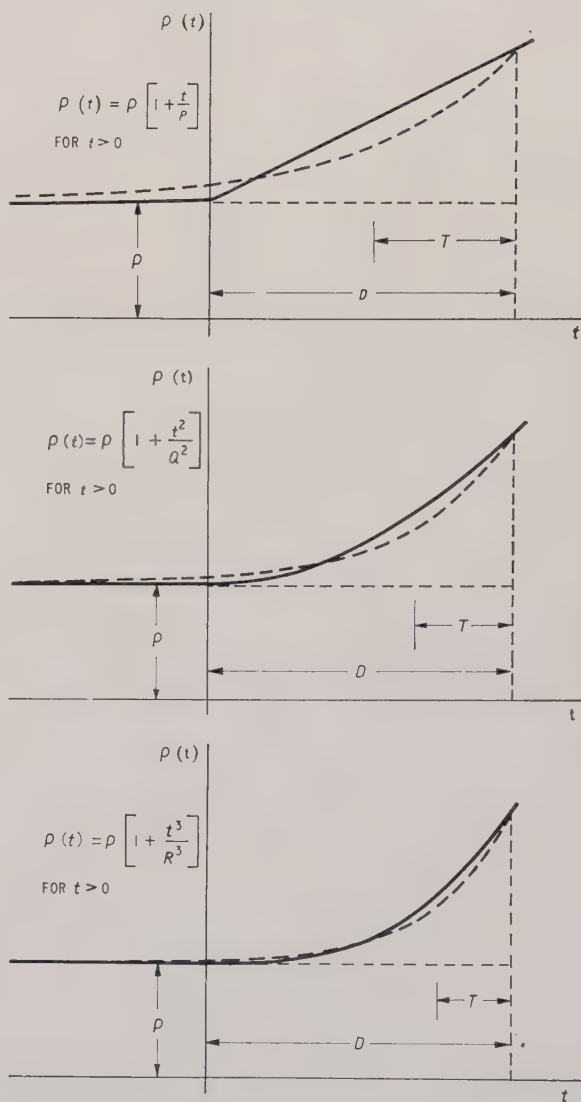


Fig. 13. Diode pump time-constant T to give optimum response to a linear rise, a parabolic rise and a cubic. The dotted curve is an exponential one, in each case, increasing by the factor e in the time T .

same as the power of t in the excursion form. That is, the last terms are $-D/T$ and $+\frac{1}{2}D^2/T^2$, respectively. The following maxima are then found for the functions of D/T , including the fixed numerical factors:

	D/T	T/D	Maximum	Absolute optimum	Per-centage difference in D (%)
t/P	2.15	0.465	0.32279	0.33333	1
$(t/Q)^2$	3.10	0.323	0.19771	0.20000	0.23
$(t/R)^3$	4.07	0.246	0.14204	0.14286	0.082

The absolute optimum results given are obtained from eq. (4) of ref.¹), which is

$$\frac{r^2}{\rho} = \int_0^D \{ f(t) \}^2 dt .$$

(5)

In the example taken above, this gives

$$\frac{r^2}{\rho} = \int_0^D \left\{ \left(\frac{t}{R} \right)^3 \right\}^2 dt$$

$$= \frac{1}{7} \frac{D^7}{R^6}$$

(6)

and the other two figures follow similarly. Assuming exact bias at a fixed value K of the significance factor r , and bearing in mind the power of t concerned in each case, one obtains the figures given for the percentage increase in D due to the departure from the absolute optimum condition involved in the use of the diode pump circuit. The relationship between the weighting function and the form of the excursion for each of the optimum values of T/D listed above is shown in fig. 13.

Appendix 3

THE LIMITING SITUATION WHEN M TENDS TO 0*near bias approximation case*

Assume that the bias applied is of the form

$$\Delta N = \alpha + \beta N$$

is 62.5 and β is 0.2 for the circuit described). In this case, assume $\sqrt{\alpha/M} \gg 1$. Let $B = \sqrt{\alpha/M}$. Then

$$\begin{aligned}\beta N &= \beta \rho T \\ &= \beta \rho BP \\ &= \beta \rho P \sqrt{\alpha/M} \\ &= \beta M \sqrt{\alpha/M} \\ &= \beta \alpha \sqrt{M/\alpha}\end{aligned}$$

$$\alpha + \beta N = \alpha (1 + \beta/B).$$

The bias is therefore an approximation to α input pulse increments. For the excursion to overcome this bias, therefore,

$$\begin{aligned}+ \beta/B) \alpha &= \int_0^D \rho e^{t/P} e^{-(D-t)/T} dt \\ &= \rho e^{D/P} \int_0^D e^{-(D-t)/P} e^{-(D-t)/BP} dt \\ &= \rho e^{D/P} \int_0^D e^{-t'/P} e^{-t'/BP} dt' \\ &= e^{D/P} \rho P \left(1 + \frac{1}{B}\right)^{-1} [1 - e^{-D(1+1/B)/P}].\end{aligned}$$

Since $B = \sqrt{\alpha/M} = \sqrt{\alpha/\rho P}$ and since $X = D/P$

$$(1 + \beta/B) (1 + 1/B) = (e^X - e^{-X/B})/B^2.$$

Taking the limit as $B \rightarrow \infty$

$$\begin{aligned}X &= \log_e B^2 \\ &= \log_e (\alpha/M).\end{aligned}$$

This corresponds to the detection of the first α

pulses (63 in practice) in the excursion. The value of B chosen ($\sqrt{\alpha/M}$) is such that:

- $T/P = B \rightarrow \infty$ as $M \rightarrow 0$
- $N = BM \rightarrow 0$ as $M \rightarrow 0$.

These two conditions together ensure the optimum performance for very low M . If the condition (a) does not apply, there will be appreciable leakage from the storage condenser during the excursion and therefore more than α input pulses will be required to overcome a bias of α pulse increments. If the condition (b) does not apply, the bias of $\alpha + \beta N$ pulse increments will be appreciably more than α such increments and therefore more than α input pulses will be required to overcome it. It is therefore clear that the requirement of α input pulses for values of B such as that given above is the optimum.

Diode pump case with exact bias

Since $T = P$ in this case, $B = 1$ and $N = M$. The bias required therefore becomes $K \sqrt{\frac{1}{2}M}$ pulse increments, which can be less than one pulse increment, for a sufficiently small value of M .

Absolute optimum case

Since this case coincides with the case above, for sufficiently small values of M , the results for that case may be applied immediately. Alternatively, the same result may be obtained by considering the absolute optimum weighting function

$$w'(t') = \frac{(e^{(D-t')/P} - 1)}{(e^X - 1)}$$

which applies in this case. The standard deviation can then be obtained in terms of M and X from this function $w'(t')$ by the method given in ref.¹), for finite values of M , and becomes $\sqrt{\frac{1}{2}M}$ in the limit, as above.

A PRECISION CURRENT INTEGRATOR

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A precision current integrator has been developed to measure the mean current from a fission chamber in a zero power reactor over each of a sequence of equal time intervals and in this way to give an accurate determination of a long period, in spite of the statistical fluctuations in the fission chamber current. This integrator was required to facilitate reactivity measurements on small samples of material in the experimental reactor VERA. The integrator and its associated electronic

equipment are described. The latter includes a counter-balancing current source for backing off a large part of the fission chamber current and a crystal-controlled timer giving alternative integrating intervals of 50, 100 or 200 s. The accuracy of the mean current measurements, relative to each other, is of the order of $\pm 0.02\%$, which is comparable with the limit set by the inherent statistical error of the fission chamber current.

1. Introduction

This current integrator was developed to determine the perturbation or change in reactivity of a critical assembly, due to the insertion of a given sample of material into the core. The technique consists basically of measuring the period accurately both before and after the insertion of the sample and calculating the change in the reactivity from the results obtained. The period is determined by accurately measuring the mean value, for each of several successive time intervals, of the current from a fission chamber in or near the core.

Provided that the reactor has been left without any appreciable disturbance for a sufficient time for any higher modes present to die out, it will assume a state in which the fundamental mode predominates. The neutron flux at any part of the reactor is then proportional to an increasing or decreasing exponential function of time $e^{t/\tau}$. The value of the period τ depends upon the control rod position and the samples in place, if any. It follows that the ion chamber current is proportional to the same exponential function, apart from a superimposed random fluctuation due to the detection of individual neutrons. If $I_f(t)$ is the expected value of the chamber current at time t (ignoring the fluctuation current), we have that

$$\log_e I_f(t) = \log_e I_f(0) + t/\tau. \quad (1)$$

If there were no statistical fluctuations in the ion chamber current, it would only be necessary to measure it with sufficient accuracy for a sequence of values of t . If the logarithm of the current was found to be a linear function of time, it would be known that the higher mode components had become negligible, and τ could be calculated.

Consider now the integrated current or total charge passed by the chamber in an interval of duration D seconds centered on a time t' . This total charge is given by

$$\begin{aligned} \int_{t'-\frac{1}{2}D}^{t'+\frac{1}{2}D} I_f(0) e^{t/\tau} dt &= I_f(0)\tau(e^{(t'+\frac{1}{2}D)/\tau} - e^{(t'-\frac{1}{2}D)/\tau}) \\ &= I_f(0)\tau(e^{D/2\tau} - e^{-D/2\tau}) e^{t'/\tau} \\ &= \tau(e^{D/2\tau} - e^{-D/2\tau}) I_f(t'). \end{aligned}$$

Strictly speaking, a term for the integrated fluctuation current should be added to this, but the expected value of this term is zero and the random charge fluctuation from it is much smaller as a proportion of the total charge than the instantaneous fluctuation current is of the expected current $I_f(t)$. This term is therefore omitted.

The coefficient of $I_f(t')$ in eq. (2) (which approximates to D , for $D \ll \tau$) is a function of D and τ only. It follows that, if the integrated current is measured over a series of equal intervals of duration D , the charge in each case is proportiona

at the middle of the corresponding period. Since the check for the decay of the higher modes and the calculation of τ may be carried out as described above, with the advantage that the random fluctuations are greatly reduced by the action of the integrator. The maximum reduction of the

unaffected. A simplified block diagram for the whole equipment is shown in fig. 1.

2. Principle of the Current Integrator

The current integration is obtained by means of a low-leakage capacitor and a stable direct-current

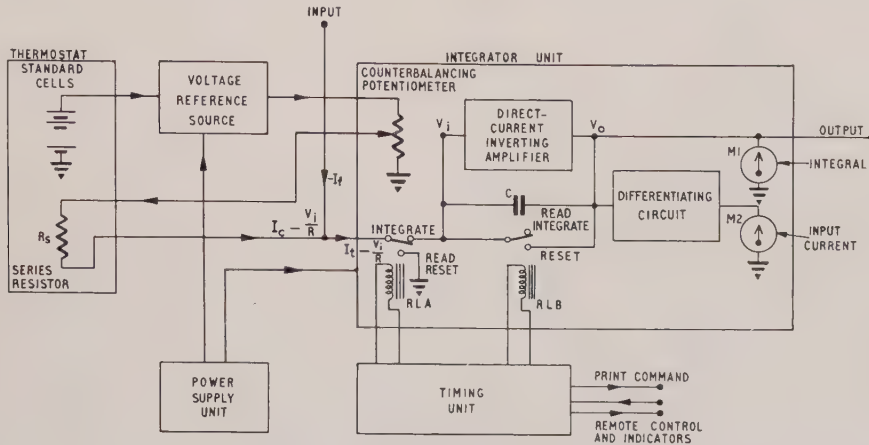


Fig. 1. Simplified block diagram of the whole equipment.

random fluctuations is, of course, to be obtained by using the largest value of D permitted by the chosen spacing in the successive values of t' . For this reason, the equipment is arranged to commence a new integrating interval as soon as the integrator has been read and reset. The necessary timing can be obtained with very high accuracy by reference to a crystal-controlled oscillator incorporated into the equipment.

The reactor periods in these experiments are very long compared with the integrating time intervals required (50, 100 or 200 s) or even with the total measuring time for each setting of the reactor. The fractional changes in the fission chamber current in such case are therefore small. It has been found to be practicable to subtract a fixed direct current from the ion chamber current, before integrating the latter. Since such a current may be maintained constant with very high accuracy, it is useful to balance out most of the chamber current in this way, leaving only a small part to be measured by the integrator and reducing the demands on the accuracy of the latter. Provided that the current subtracted is accurately allowed for, by means of a suitable calibration of the current source against the integrator, or vice versa, the above theory is

inverting amplifier, as shown in fig. 1. As is well known, such a circuit gives an integrating action with a virtual earth at the input terminal of the amplifier. Since the input impedance of the amplifier is very high, consisting effectively of a very high resistance in parallel with a small stray capacity, and since the voltage at the input terminal only changes relatively slowly, it is permissible to neglect the input current to the amplifier. (The conditions of operation of the first valve are chosen to give negligible grid current.) It follows that the current through the integrating capacitor must equal the total input current precisely. The total charge in the capacitor, which is the integral of this current, is equal to $(V_i - V_o)C$ where V_i is the voltage at the input terminal and V_o is the voltage at the output terminal. Since the virtual earth action keeps V_i very small, the total integrated current at any time approximates closely to $-V_oC$. (The negative sign arises because the current flows into the capacitor at the virtual earth terminal.) It is clear that this action does not depend critically upon the gain or linearity of the amplifier, so long as its gain is sufficiently high. A more detailed analysis of the integrating action follows.

2.1. THEORY

The relationship between the output voltage V_o and the input voltage V_i of the direct-current amplifier, within the range of output voltages for a linear output (-10 V to $+10$ V is actually used) is of the form

$$V_o = -AV_i + K \quad (3)$$

when no load current is drawn from the output terminal. Since the output impedance of the amplifier is of the order of 200Ω and since the maximum input current to be accepted is of the order of 2×10^{-8} A, the maximum loading effect upon the output is equivalent to 4×10^{-6} V in K , which is completely negligible, so that the above eq. (3) applies unmodified. If I_i is the actual input current and C is the capacity of the integrating capacitor, we then have the relationship

$$\begin{aligned} I_i &= \frac{d}{dt} C(V_i - V_o) \\ &= \frac{d}{dt} C(V_i + AV_i - K) \\ &= C(A + 1) \frac{dV_i}{dt} \end{aligned} \quad (4a)$$

$$= -C(1 + 1/A) \frac{dV_o}{dt} \quad (4b)$$

This represents a perfect integration of the input current I_i . If the input current were derived from a source of infinite impedance, no further qualification would be needed.

The fission chamber itself does effectively represent an infinite impedance, since any changes in V_i (of millivolt order) have an entirely negligible effect on the current through it. However, the series resistor ($24\text{ M}\Omega$) which is used to supply the counterbalancing current presents a conductance which is not negligible, although it is small. The counterbalancing circuit may be regarded as an infinite impedance source of current I_c in parallel with a resistance R , where R is its output resistance. Precisely

$$R = R_s + R_p \quad (5)$$

where R_s is the resistance of the series resistor and R_p is the output resistance of the potentiometer, which is relatively small and is kept effectively

constant by a compensating device, as the setting is varied. If the fission chamber current is negative and is $-I_f$, it follows that the fission chamber and counterbalancing circuit together represent an infinite impedance source of a current.

$$I_t = -I + I_c \quad (6)$$

in parallel with the resistance R .

It follows that

$$I_i = I_t - V_i/R \quad (7)$$

and from eq. (4a) this gives

$$\begin{aligned} C(A + 1) \frac{dV_i}{dt} &= -I_f + I_c - V_i/R \\ \therefore \frac{dV_i}{dt} + \frac{V_i}{RC(A + 1)} &= -\frac{1}{C(A + 1)} (I_f e^{t/\tau} - I_c) \end{aligned} \quad (8)$$

where I_f is the value of I_f at $t = 0$, assuming that the single mode condition has been reached at the time $t = 0$. Let $T = RC(A + 1)$. Then multiplying both sides of equation (8) by $e^{t/T}$,

$$e^{t/T} \frac{dV_i}{dt} + \frac{e^{t/T} V_i}{T} = -\frac{e^{t/T}}{C(A + 1)} (I_f e^{t/\tau} - I_c)$$

Integrating from $t' - \frac{1}{2}D$ to $t' + \frac{1}{2}D$

$$\begin{aligned} \left[e^{t'/T} V_i \right]_{t' - \frac{1}{2}D}^{t' + \frac{1}{2}D} &= -\frac{I_f}{C(A + 1)} \frac{1}{\frac{1}{T} + \frac{1}{\tau}} \left[e^{(t'/T + t'/\tau)} \right]_{t' - \frac{1}{2}D}^{t' + \frac{1}{2}D} \\ &\quad + \frac{I_c T}{C(A + 1)} \left[e^{t'/T} \right]_{t' - \frac{1}{2}D}^{t' + \frac{1}{2}D} \end{aligned}$$

Assume that the initial value of V_i at $t = t' - \frac{1}{2}D$ is V'_i , which is small compared with its final value. Then

$$\begin{aligned} e^{t'/T} \{ V_i e^{D/2T} - V'_i e^{-D/2T} \} \\ = -\frac{I_f}{C(A + 1)} \frac{e^{(t'/T + t'/\tau)}}{\frac{1}{T} + \frac{1}{\tau}} [e^{(D/2T + D/2\tau)} - e^{-(D/2T + D/2\tau)}] \\ + \frac{I_c T}{C(A + 1)} e^{t'/T} [e^{D/2T} - e^{-D/2T}] \end{aligned}$$

Since $D/T \ll 1$ and $V'_i \ll V_i$, the term in V'_i may be taken as $V'_i e^{D/2T}$, without serious error. This gives

$$e^{D/2T} (V_i - V'_i) = \frac{D}{C(A + 1)} (-\theta_1 I_f e^{t'/\tau} + \theta_2 I_c) \quad (9)$$

re

$$\tau_1 = 1 + \frac{1}{3!} \left(\frac{D}{2T} + \frac{D}{2\tau} \right)^2 + \frac{1}{5!} \left(\frac{D}{2T} + \frac{D}{2\tau} \right)^4 + \dots$$

$$\theta_2 = 1 + \frac{1}{3!} \left(\frac{D}{2T} \right)^2 + \frac{1}{5!} \left(\frac{D}{2T} \right)^4 + \dots$$

It follows that

$$I_f' e^{t'/\tau} = \frac{C(1 + 1/A)e^{D/2T}}{\theta_2 D} (V_0 - V_0') + I_c \quad (11)$$

where $V_0' = -AV_i' + K$.

Rearranging this and putting $I_f = 0$ for the case of zero fission chamber current during calibration

$$I_c = -\frac{C(1 + 1/A)e^{D/2T}}{\theta_2 D} (V_0 - V_0'). \quad (12)$$

Now the coefficient of $(V_0 - V_0')$ in eqs. (11) and (12) is the same and depends on D only, apart from the circuit parameters, and not on τ . Therefore, provided that the calibration is made for the same value of D as is to be used in the experiment concerned, it is possible to calibrate the integrator in terms of the equivalent counterbalancing current (or in terms of the potentiometer reading, which is proportional to the current). This calibration is carried out in practice by adjusting the value of R_s for each of the three possible integrating times, so that the readings of the counterbalancing current potentiometer and of the integrator are in exact agreement and no arithmetical corrections are needed. The factor θ_1/θ_2 which is the coefficient of $I_i' e^{t'/\tau}$ in eq. (11), does not matter, as it is constant for a pure exponential excursion with a given value of τ , and it is not necessary to find the value of I_i' .

ZERO ADJUSTMENT OF THE AMPLIFIER

If the input terminal of the integrator is disconnected from external current sources, but connected to the output terminal directly, by a switch, a steady condition is very rapidly reached, in which the constraint $V_i = V_0$ applies. This arrangement of the integrator is provided by the controlling timer immediately before each integration commences and is referred to as the RESET

condition. It follows from eq. (3) that in this condition

$$V_i = V_0 = \frac{K}{1 + A}.$$

The amplifier includes a potentiometer which varies K and, if this is adjusted to make V_0 precisely zero in the RESET condition, K becomes zero. If the switch across the capacitor is opened, with the input current sources still disconnected, the amplifier retains its steady values of V_i and V_0 . This condition of the integrator is referred to as the READ condition, since it is normally provided by the timer at the end of each integration, for the reading to be taken. (It therefore precedes the RESET condition in the normal cycle.) The fact that no drift is obtained with $V_0 = 0$ in the READ condition is a confirmation that no appreciable grid current is flowing in the first valve, as this would cause a steady drift. The fact that no drift occurs in the READ condition for other values of V_0 is a confirmation of the very high leakage resistance of the integrating capacitor.

Since K is adjusted to be zero and since the switching arrangements are such that V_i and V_0 do not alter during the transition from RESET to INTEGRATE, each integration starts with V_i and V_0 both zero. The most sensitive indication of the correct adjustment of K is actually obtained by reference to the value of V_i at the beginning of an INTEGRATE period. For this adjustment, the fission chamber should be disconnected and the potentiometer of the counterbalancing circuit should be set to zero. If there is a drift, when the INTEGRATE period starts, this is an indication that V_i , and therefore K , is not zero and the potentiometer controlling K should be adjusted accordingly. Since this is the most sensitive indication, V_0 should always read zero in the RESET condition, when this adjustment has been made properly.

3. General Description of the Instrumentation

Reference to the block diagram, fig. 1, shows that there are five main components of the system. They are:

1. The current integrator unit.

- 6. The power supply unit.
- 7. The timing unit.
- 8. The voltage reference source.
- 9. The voltage reference source standard cell thermostat.

A differentiating circuit is also provided in the integrator unit, operating from the output of the integrator. It provides a measure of the rate of change of the integral, which is to say, a measure of the current being integrated. It is more convenient for this purpose than a galvanometer or similar device measuring the current directly. The timing unit controls the integrating period and the time intervals between successive integrations. The stage reference source and the standard cell unit together provide a constant voltage, from which is derived the backing-off current. The standard cell unit is enclosed in a constant-temperature bath, which also contains the series resistor which regulates the backing-off current.

Current Integrator Unit

The circuit of this unit is given in fig. 2. The operation of the unit can best be explained by subdividing it into two main parts. The valves V1 to V8 constitute the integrator proper. The valves V6 and V8 form the differentiating amplifier. A stabilised water supply is used for the whole unit, as well as stabilised positive and negative supplies, in order to maintain the parameters of both amplifiers as constant as possible. All these supplies are obtained from the current integrator power unit.

INTEGRATOR

V1 is a double triode, connected as a long-tailed pair amplifier and operating under conditions chosen to give a low grid current. It is found that a low value of grid current implies a low anode current, a low anode current and a cathode temperature that is lower than the normal. The anode voltage used is 50 V and the anode current is 10 μ A. The heater voltage applied is 8 V, which is 1 V for each section (instead of the normal 6.3 V). V2 and V3 are again double triodes used in the conventional long-tailed pair configuration. The circuit is designed so that each long-tailed pair operates as near as possible to its symmetrical

condition, to minimize the effect, for example, of any residual heater voltage variation. The first half of V4 is a conventional amplifier, while the second half functions as a cathode-follower with some local negative feedback from the cathode of V4b via the potential divider consisting of R42 and R34 to the grid of V3b. V4 is followed by V5a, a conventional amplifier, and V5b, the cathode-follower output stage.

The cathode of V5b is connected to the grid of V1a by the integrating capacitor C14, which has a polystyrene dielectric for low leakage. Direct interval coupling is used throughout the amplifier and the high-frequency response of each coupling potential divider is maintained by the addition of a small capacitor in parallel with the top arm of the divider. For example, the interval coupling from V2a to V3a consists of the potential divider R23 and R26, R23 being by-passed by C3, a 100 pF capacitor. The components C6, C8 and R55 in the interval coupling from V5a to V5b ensure the stability of the amplifier by reducing the loop gain to less than unity at frequencies where the phase shift is pronounced. The gain within the pass band is 3000.

The output of the integrator is indicated on the centre-zero meter M1 or can be measured at the terminals T₁ and T₂ or at the socket SKT1. All the relays are shown in the de-energised position, which corresponds to the INTEGRATE mode of operation. This arrangement has the possible slight advantage that the integrator continues to function as such, without modification, when it is used without the timing unit. As already stated, there are three distinct modes, all controlled from the timing unit, and these can be selected by a switch or set to cycle automatically. They are:

1. INTEGRATE
2. READ
3. RESET

In the INTEGRATE mode, the two relays RLA and RLB are de-energised and the fission chamber current flows via PL1 and the contact RLA-1 to the integrating capacitor C14. The backing-off current is of opposite sign to the fission chamber current and is derived in the following manner. The 24 V reference from the voltage reference source is

applied to the resistor network R94 to R138 via the plug PL2. A fraction of this, selected by the switches S1 and S2 and the helical potentiometer RV7, is then taken (via the switch S3, one of the pre-set potentiometers RV8, RV9 or RV10, and SKT3) to one end of the $24\text{ M}\Omega$ resistor, the other end of which is connected (via SKT3 pin A) to the input terminal of the integrator. The integrating capacitor C14 receives the difference between these two currents and proceeds to charge. Section C of the switch S1 and the resistors R135 to R138 associated with it ensure that the output impedance of the whole potentiometer system remains approximately constant at all settings.

After an interval, determined by the timing unit, the INTEGRATE mode is terminated and the READ mode begins. In this mode, the relay RLA is energised, the difference current flows to earth via the relay contact RLA-1 and the charge acquired by the capacitor C14 is held constant while the output voltage at T1 and T2 is measured. At the end of the READ mode, again determined by the timing unit, the RESET mode is initiated and the relay RLB is energised, discharging the integrating capacitor C14 via the contact RLB-1 and the resistor R87, and so preparing the circuit for the commencement of another integrating period.

The three separate preset potentiometers RV8, RV9 and RV10 are provided so that the necessary calibration adjustment can be made for each of the three integrating times, in turn, without disturbing the settings for the other two. In order to obtain a correction for the variation with D of the factor $e^{D/2T}/\theta_2$, which appears in eq. (11), while still retaining a suitably fine adjustment, the rheostats RV9 and RV10 are used with extra, fixed resistors ($130\text{ k}\Omega$ and $200\text{ k}\Omega$, respectively) in series with them. These resistors are situated in the thermostat, for maximum stability, and three separate connections to the thermostat are therefore provided for the three rheostats, so that the appropriate fixed resistance is automatically selected when the switch S3 is set.

4.2. DIFFERENTIATOR

This circuit operates as a conventional virtual-earth differentiating amplifier. V6 and V7 are two

cascaded long-tailed pairs, with V8a as a direct current amplifier and V8b as a cathode-follower output stage. The overall gain of the amplifier is about 1500. The differentiation components are C17 and R91, while the resistor R57 ensures stability against oscillation of the differentiator. The output of the integrator is applied, from the cathode of V5b, via R57 to the differentiating capacitor C17. The maximum current drawn by this capacitor occurs when the integrator output reaches its full value of 10 V in the minimum integrating time of 50 s, $2 \times 10^{-7}\text{ A}$. This load only alters the output voltage of the integrator by $200 \times 2 \times 10^{-7}/3000 = 1.3 \times 10^{-8}$, which is negligible. The reading of the centre-zero meter M2 is then proportional to the differential of the integrator output and is therefore proportional to the magnitude of the difference current flowing into the integrator. Owing to the random fluctuations of the fission chamber currents some damping is required in the differentiator, so that M2 indicates the mean recent value of the difference current, rather than its instantaneous value. This damping is provided by the capacitor C17 in parallel with the resistor R91. It is of considerable assistance to the reactor operator to have a direct indication of the difference current immediately available, by this means, apart from the more precise information provided by the integrator. The potentiometer RV6 is adjusted to give a full-scale deflection of M2 for a difference current of 10^{-8} A . A 100 mV recorder can be connected to SKT2 which, for zero difference current, has a steady potential of 50 mV, set by RV4, and varies from 0 to 100 mV for integrator input currents in the range -10^{-8} to $+10^{-8}\text{ A}$. The relay contact RLB-2 reduces the sensitivity of the differentiator during the RESET mode, so that the rapid discharge of C14 when the contact RLB-1 closes is not interpreted as a very large difference current by the meter M2.

4.3. GENERAL CHARACTERISTICS OF THE INTEGRATOR

The maximum current that can be integrated is that which produces a full-scale output from the meter M1 in the selected integration time. This corresponds to the capacity C of the capacitor C

minally $0.1 \mu\text{F}$) being charged to a potential of 10 V . For the 100 s integration period, this current (measuring C in microfarads)

$$\frac{10 \times 10^{-6} C}{100} \text{ A} = \frac{C}{10} \mu\text{A}.$$

This is nominally 10^{-8} A . For the 50 s and 200 s integrating periods, the corresponding currents are twice and half this, respectively. Any deviation of the capacity (and therefore of the currents) from the nominal value is of no importance in the intended use of the integrator, but the actual value of the capacity should be accurately measured and allowed for, if the integrator is required to measure the currents instead of relative values. The backing-off current is continuously variable from 10^{-8} A to about 10^{-6} A , being read in potentiometer units of a nominal value of 10^{-7} A . The total range is therefore 0 to 10 of these units and the setting of the potentiometer may be read to the nearest division of the helical potentiometer, which provides the fine control. Each of these divisions represents 0.0001 of a unit. The actual value of these units is adjusted in practice to be very close to $C \mu\text{A}$ so that full-scale outputs of the integrator in 50 s , 100 s and 200 s correspond precisely to 0.2 , 0.1 and 0.05 potentiometer units, respectively. This adjustment is made by means of the rheostats RV8, RV9 and RV10 and is done in such a way as to correct for the factor $(1 + 1/A) e^{D/2T/\theta_2}$ which appears in eqs. (11) and (12) and which is very close to unity.

The maximum output voltage at the terminals T1 and T2 is 1.0 V (+ or -), corresponding to the full-scale deflection at 10 V of the meter M1. The potentiometer formed by the resistors R88 and R89 is designed to give a voltage of $0.1 V_0$ at the terminals, for measurements by a precision potentiometer. It should be free from any drift in the dividing ratio, since the temperature coefficients of the two resistors are the same, and any error in the dividing ratio is compensated for in the calibration of the integrator. The output impedance is 1800Ω or 1.1% . The integrator output V_0 may alternatively be read directly by a digital voltmeter, preferably of 0.01% accuracy, reading up to 10 V . (The socket SKTI is provided for con-

necting such a voltmeter.) In either case, of course, the calibration of the integrator against the backing-off potentiometer should be carried out using the system of output measurement that is to be used in the actual experiment. The timing unit provides alternative READ intervals of 25 s and 3.125 s , for use with a precision potentiometer and a digital voltmeter, respectively. The RESET interval is 1.5625 s . These times are nominal only, as they refer to the timing of the signals applied to the relays concerned and not to the actual operation of the relays. However, the duration of the overall cycle is the precise sum of these nominal times, apart from any variation of relay operating times from one cycle to the next, which is less than $\pm 1 \text{ ms}$ and is therefore quite negligible. The exact duration of the READ and RESET intervals is not important. The effect of the relay operating times on the INTEGRATE interval is to make it 64 ms less than its nominal value, in all three cases. This is automatically compensated for in the adjustment of RV8, RV9 and RV10, when the integrator is calibrated in accordance with the instructions. (It would involve a very small additional correction in true current measurements, as would any error in the ratio of the divider R88 and R89, if used.)

4.4. CALIBRATION ADJUSTMENT

To obtain the highest possible accuracy from this equipment, the operator should make the following checks and adjustments each time that it is used.

1. With the power off, check that the mechanical zeros of the meters M1 and M2 are correct. (These should not normally require readjustment.)

2. Switch the power on for at least one hour for conditions to stabilise. The fission chamber should be disconnected during the calibration.

3. Set the control switch on the timing unit to hold the integrator in the RESET condition. Adjust the potentiometer RV3, M2 ZERO, until M2 reads zero.

4. Set the timing unit to cycle normally with an integrating time of 50 s and a reading time of 25 s . Set the counterbalancing potentiometer precisely at zero. Adjust the potentiometer RV1, M1 ZERO so that there is no drift of the reading of M1 during each integrating period. The most sensitive im-

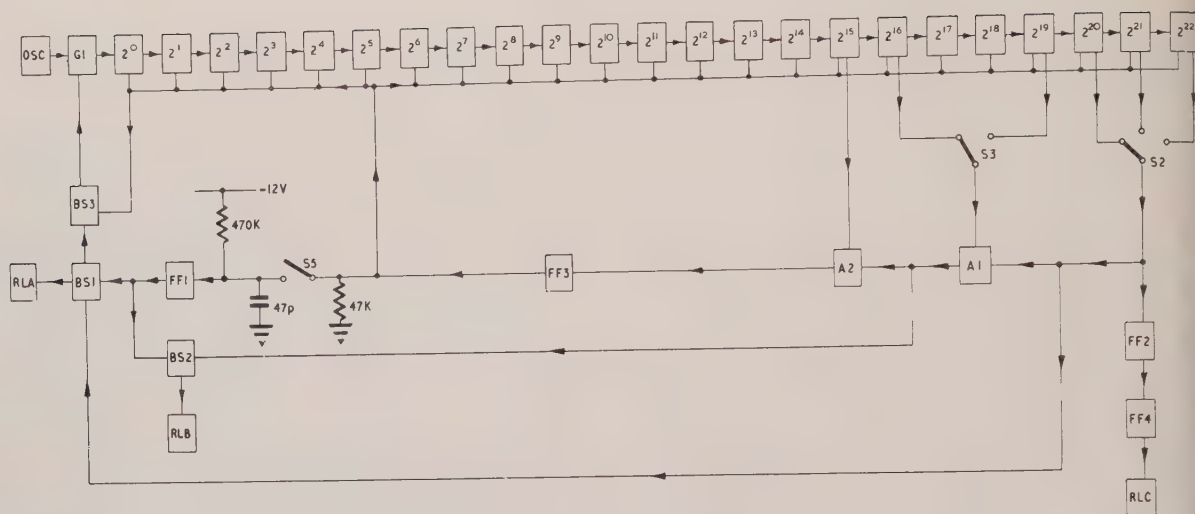


Fig. 3. Transistor timing unit block diagram.

mediate indication of the correct adjustment is that the meter M2 should continue to read zero during the integrating period.

5. An even more sensitive indication should then be obtained by integrating for 200 s and reading the output voltage on the precision potentiometer (or a digital voltmeter). The integrated output will be a linear function of the setting of RV1 and it is therefore possible to obtain a rapid convergence to the correct zero adjustment by linear interpolation between readings taken or by reference to the fact that the integrated output for a 200 s period is varied at the rate of approximately 2.00 V per turn of RV1. Alternate readjustments and integrations should be continued until the integrations give zero output.

6. The counterbalancing potentiometer should be set at the precise position to give full-scale output on the integrator for the integrating period to be used. For example, this is 0.1 units (nominally 10^{-8} A) for the 100 s period. The selection switches on both the integrator and the timing unit should be set to this period. This current should then be integrated and the appropriate preset calibration control adjusted, alternately, until the integrator output voltage after each integration is precisely 10 V, by the measuring device to be used. A quarter turn of the control should alter the value of V_0 obtained by approximately 10 mV.

7. If a recorder is being used with the differen-

tiator, set the integrator control to the RESET condition and adjust the potentiometer RV2 RECORDER ZERO to give mid-scale reading of the recorder. This adjustment may interact slightly with that of RV3, M2 ZERO, which is made in the same condition, and if necessary each potentiometer should be adjusted in turn until both are correct.

8. The equipment is then ready for use and the fission chamber may be connected.

If the equipment is in regular use and is allowed ample time to warm up on each occasion, before any adjustments are attempted, the amount of readjustment needed will be minimised.

4.5. POWER SUPPLY UNIT

This unit contains two commercial sub-units supplying 50 mA at +300 V and 50 mA at -300 V, respectively, both voltages being stabilised. A stabilised supply of 150 mA at 96 V is also provided, for the heaters of the integrator unit which are in series. The stabiliser used is a simple one of standard two-valve type. The power supply unit also incorporates a 12 V, 200 mA supply for the relays.

5. Timing Unit

Referring to the block diagram, fig. 3, the cycle of events is started by closing the switch S5, which triggers the flip-flop FF1 and, 20 μ s later, the

able circuits BS1 and BS2. The relay RLA is energised from BS1 and the relay RLB from BS2. The corresponding slave relays A and B in the current integrator are thereby de-energised and the integration period commences. When the bistable circuit BS1 is triggered, a pulse is passed to the bistable circuit BS3 controlling the gate G1, which triggers that circuit and opens the gate. The oscillator pulses at a repetition frequency of 20.971 kc/s are then allowed through G1 and are filtered by the scaling stages 2^0 to 2^{22} . The switch S3 determines the integrating time and the first positive step passed by S2 (in the switch position shown this is 50 s after G1 is opened) is differentiated to a positive pulse at BS1 and turns the latter off, thus de-energising the relay RLA, de-energising the slave relay A in the integrator unit and initiating the READ period in the latter unit. BS1 is turned off, FF2 is triggered and 100 ms later (to allow for relay operating times) FF4 is triggered and the relay RLC is energised for 1 s, providing the print command signal for a print-out voltmeter, if one is connected.

The switch S3 determines the time available for read-out (in the switch position shown, this is 25 s) and when the output voltage from both this switch and S2 is at the more positive of the two possible levels, the output of the direct-current AND circuit A1 takes a more positive level. This change of level occurs as a sudden positive step, which is differentiated at BS2 and turns the latter off, de-energising the relay RLB, energising the slave relay B in the integrator unit and discharging the integrating capacitor. 1.5625 s after BS2 is turned off, that is, when the output of A1 and the 2^{22} stage are both at their more positive level, the output of the AND circuit A2 also moves positively. This step is differentiated and triggers FF3, which provides a 13 μ s reset pulse to all of the scaling stages and to the bistable circuit BS3 controlling BS1. FF1 is also triggered from FF3 and so, after a delay of 20 μ s, to allow the resetting action on BS3 to be completed, another cycle of events is started and repeated indefinitely, until S5 is opened. As it is only closed for 20 μ s in each complete cycle, the gate G1 does not perform any useful function, strictly speaking, while the unit is recycling. It does

however give a clean starting and stopping action, under the control of S5. A reset button is provided, which must be pressed before S5 is closed to start the cycling, in order to ensure that the bistable circuits BS1 to BS3 and the scaling stages all start from their correct states. This reset button has two contacts, one of which produces a pulse which triggers FF3. The other contact is used to open-circuit bleeders in BS1 and BS2 and thereby bias them into the correct states.

The accuracy of the overall cycle of the timer is very good. Apart from any variation in the time of operation of the same relay from one operation to the next, which is very small, the only appreciable source of error should be deviations of the crystal-controlled oscillator from its nominal frequency of 20.971 kc/s. The manufacturers state that the crystal has a tolerance of $\pm 0.005\%$ at 20°C and that its temperature co-efficient is $6 \times 10^{-6}/^\circ\text{C}$. Since any fixed error in the overall cycle time would have only a proportionate effect on the value of any period determined, it is clear that this source of error is negligible. It is also clear that, with this very low temperature coefficient, any possible drift in the duration of the integrating interval from one cycle to the next would have an entirely negligible effect on the integrator readings. The actual integrating times obtained from the timer have been measured and found to be 64 ms (± 1 ms) less than their nominal values in all three cases, due to the relay operating times, as already stated.

As this unit consists entirely of transistor circuits of standard types, connected together in the manner indicated in fig. 3, the details of these circuits are not described here.

6. Voltage Reference Source

Referring to the circuit diagram, fig. 4, the valves V1 to V3 of this unit are long-tailed pairs operated in cascade, with V4 as a cathodefollower output stage. The first long-tailed pair, V1, is designed to operate under conditions to give low grid current, that is, with low anode voltage and low anode current. The primary reference voltage obtained from the standard cell unit (approximately 24 V, see below) is applied to the grid of V1a, while the secondary reference voltage taken

from the cathodes of V4 is applied to the grid of V1b. The valve V1 then acts as an error amplifier, with its output further amplified by the cascaded long-tailed pairs V2 and V3 to provide an error signal at the grids of V4, which will maintain the cathodes of V4 close to the primary reference voltage. The overall gain is a-

cells, Muirhead type D-698-A, having an e.m.f. of $1.01859 - 10^{-6} [40.6(T - 20) + 0.95 (T - 20)^2 + 0.01 (T - 20)^3] \pm \frac{110 \times 10^{-6}}{95 \times 10^{-6}}$ V, where T is the temperature in degrees celsius. The twenty four cells, together with the 24 M Ω (nominal) resistor which, in conjunction with the secondary reference

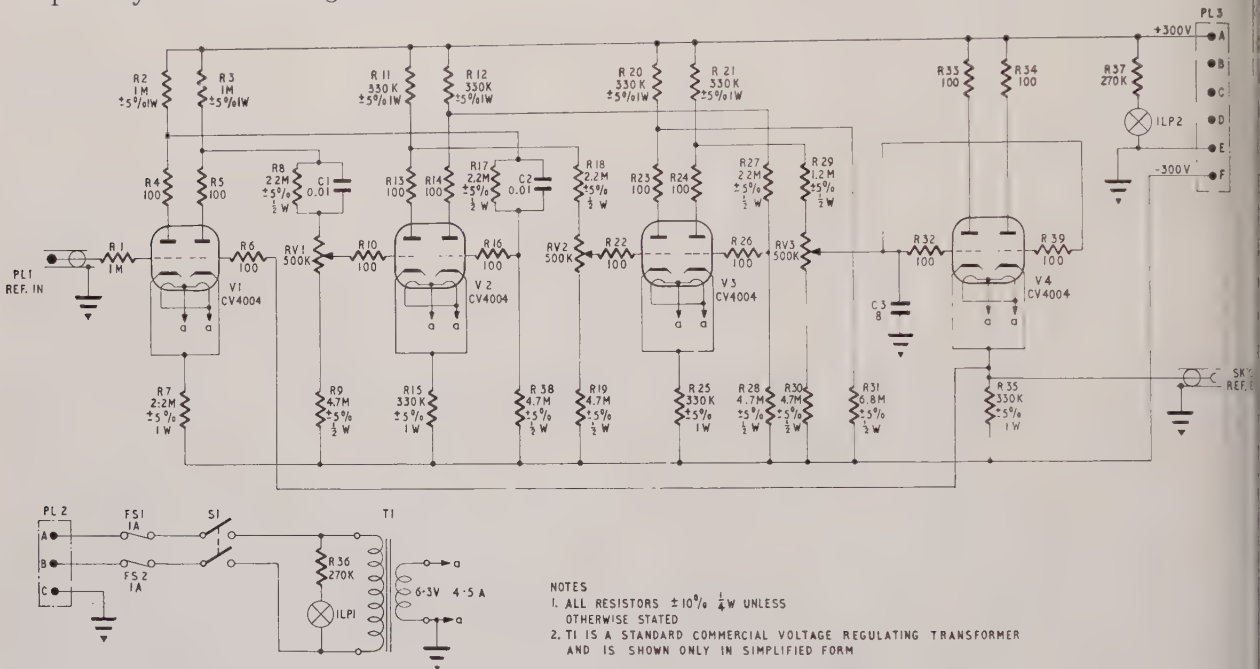


Fig. 4. Circuit diagram for voltage reference source.

about 1000. Three preset controls are provided, so that each long-tailed pair may have its anode currents accurately balanced, thus reducing the effect on the secondary reference voltage of variations in the cathode temperatures or in the high tension power supplies. It is not necessary to adjust the output voltage to be precisely equal to the input voltage or to any predetermined value, as the series resistance regulating the counterbalancing current may be adjusted to suit the actual voltage applied to the counterbalancing potentiometer. A voltage-regulating transformer, mounted in the unit, provides a stabilised heater supply for the valves V1 to V4, while the stabilised high tension supplies (+ 300 and - 300 V) are obtained from the current integrator power supply.

6.1. STANDARD CELLS AND THERMOSTAT

The primary reference voltage is derived from twenty-four, series-connected, Weston standard

voltage and with much smaller value trimming resistors and preset rheostats, defines the counterbalancing current, are mounted in a conventional temperature-controlled oil bath, which maintains them at a temperature of $30^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$. The primary reference voltage is, therefore, $(24 \times 1.018095 \pm \frac{0.00264}{0.00228})$ V, with a maximum possible variation due to oil bath temperature changes, of $\pm 300 \mu\text{V}$.

7. Accuracy

7.1. INTEGRATOR

The accuracy of the current integrator itself is estimated from drift measurements on the integrating amplifier to be of the order of $\pm 0.1\%$ of its full-scale reading, apart from the fixed error due to the difference between the actual value of the storage capacity and its nominal value, which does not matter for the present application. The measuring device for the output voltage from the in-

integrator should be capable of an accuracy of about 0.1%, to avoid an undue increase of this error. It has already been shown that drift in the duration of the integrating interval should be completely negligible and the only remaining source which might give rise to appreciable drift in the true current calibration of the integrator itself is change in the capacity of the storage capacitor with temperature. The temperature coefficient of the capacitor now in use is given as $(150 \pm 60) \times 10^{-6}/^{\circ}\text{C}$ and its temperature is not controlled at present. This arrangement is probably adequate for the present accuracy of the whole equipment, in the absence of marked changes in room temperature during an experiment, but it is proposed to use a controlled temperature in future for more accurate work.

Since the calibration of the counterbalancing current potentiometer is adjusted by reference to the readings of the integrator, by variation of the series resistance, the question of an appreciable fixed error in this calibration does not arise. It is desirable that the calibration should be carried out to an accuracy of the order of $\pm 0.01\%$, so that it does not contribute appreciably to the total error. For this reason, the three settings of the potentiometer to give the precise ratios required in this calibration are specially measured for the individual potentiometer and are to be used instead of the nominal settings for these ratios. There is, however, another source of error which must be considered. This is the departure from linearity in the potentiometer at its working setting. The potentiometer is composed of resistors of 0.1% accuracy. Some improvement in accuracy may be expected statistically, when a number of resistors are used in series, and the overall accuracy of the ratio depends on the setting. However, an error of the order of $\pm 0.1\%$ or less may be expected at normal settings.

When the integrator reading is added to the backing-off current reading, in the final calculation of an experimental mean current, there are two main possible sources of error in the relative value of the integrator contribution. These are

a. Drift in the true current calibration of the integrator.

b. Non-linearity of the backing-off current potentiometer (at a fixed setting for each period).

As discussed above, these may be expected to contribute $\pm 0.1\%$ of the full-scale reading of the integrator and $\pm 0.1\%$ of its actual reading, respectively. The largest total error expected is therefore

$$\pm \sqrt{0.1^2 + 0.1^2}\% = \pm 0.14\%$$

of the full-scale reading of the integrator.

7.2. COUNTERBALANCING CURRENT

The main possible sources of drift in the backing-off current itself are changes in the stabilised voltage applied to the potentiometer and changes in the resistance of the series resistor. The stability of the voltage reference source described above is of the order of $\pm 0.01\%$, although a somewhat more elaborate supply¹⁾ is available which could be used to give $\pm 0.002\%$. The temperature coefficient of the series resistor used at present is $400 \times 10^{-6}/^{\circ}\text{C}$. For the tolerance of $\pm 0.2^{\circ}\text{C}$ given above for the thermostat, this gives another $\pm 0.008\%$ variation. This figure could also be reduced by the use of a lower temperature coefficient resistor and/or a closer temperature control. The combined error due to these two sources of drift in the present form of the equipment is

$$\pm \sqrt{0.01^2 + 0.008^2}\% = \pm 0.013\%$$

7.3. SUMMARY

The main part of the fission chamber current will normally be counterbalanced. The drift in the counterbalancing current therefore contributes an error of $\pm 0.013\%$ to the final reading. The error of the integrator term is $\pm 0.14\%$ of its own full-scale reading. Assuming that the counterbalancing current used is at least 30 times the full-scale reading of the integrator, as will normally be the case, the latter's contribution to the final error is $\pm 0.005\%$. This gives a total error of

$$\pm \sqrt{0.013^2 + 0.005^2}\% = \pm 0.014\%$$

This accuracy appears to be sufficient for the

¹⁾ R. J. Lamden, A High Precision Voltage Reference Source, J. of Sci. Instr., to be published.

present use of the equipment, but could be improved if required, by the following straightforward steps.

- a. Temperature control of the storage capacitor.
- b. Use of closer tolerance resistors in the potentiometer.
- c. Use of the more highly stabilised voltage source.
- d. Use of a lower temperature coefficient series resistor.

These improvements could probably reduce the overall error of each integral from $\pm 0.014\%$ to about $\pm 0.005\%$. However, these errors are comparable with the limit set by the inherent statistical error of the fission chamber current, so that the value of any further improvement in the accuracy of the integral is reduced.

7.4. STATISTICAL ERROR IN THE FISSION CHAMBER CURRENT

The maximum fission chamber charge which can be measured in an integrating interval is 2×10^{-4} C, corresponding to a 10^{-6} A for 200 s. If the average charge released by each fission is taken as 5×10^{-13} C, corresponding to 3×10^6 ion pairs, this total charge implies that 4×10^8 fissions have occurred. The statistical error in this number of fissions is $\pm 2 \times 10^4$, which is $\pm 0.005\%$. This percentage error would be greater for smaller counterbalancing currents or for the shorter integrating times (inversely as the square root, in each case).

The actual figure is reduced by the fact that an

appreciable proportion of the fission fragments may be stopped by the foils at less than their full range in the present chamber. However, it is increased by the presence of reactor noise. These two effects happen to compensate each other, approximately in the present application, so that the above figure of $\pm 0.005\%$ is still roughly correct.

8. Conclusions

This integrator is a promising instrument for its intended purpose, which is to enable accurate reactivity measurements to be made on small samples of material, without the need for laborious and time-consuming readjustment of the reactor used to infinity period before and after the insertion of each sample. The accuracy of the integrator is such that any appreciable further improvement is limited by the inherent statistical error of the fission chamber current.

Acknowledgement

While the whole project has been outlined briefly in the introduction, for completeness, the present authors have been concerned only with the electronic equipment described in this paper. They wish to thank their colleague Mr. M. H. McTaggart, who is working with the experimental reactor VERA, for suggesting this problem to them. Mr. McTaggart proposed the method of reactivity measurement for which this integrator was designed and is using it for the measurement of samples in VERA.

SINGLE CHANNEL TRANSISTORIZED PULSE HEIGHT ANALYZER

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Received 5 August 1961

completely transistorized single channel pulse analyzer is described, with a dead time of 330 ns. The range on the pulses may be analyzed is 0.3 ÷ 6 V. The window width and the threshold voltage are independent and determined by the

reverse bias of two distinct diodes. The complete circuit diagram is given with a series of tests obtained with several input pulse widths up to a frequency of 2 Mc/s and for room temperatures ranging from 10°C to 40°C.

Introduction

The pulse height analyzer described here is a development of the fast transistorized pulse height analyzer we described in a previous work¹⁾ whose operation had been proposed independently by two distinct groups of researchers^{2,3)} some years ago. The analyzer described in this work is characterized by the following operation: a threshold discriminator is fed by a pulse of amplitude V_0 and by another one delayed by a time τ with respect to V_0 whose amplitude is $(V_0 - V_c)$. V_c is a constant potential difference. The threshold discriminator gives either one, two or else no output according to one of the following cases:

Input pulse amplitude	Number of output pulses from the threshold discriminator
1) $(V_0 - V_c) < V_t < V_0$	1
2) $V_t < (V_0 - V_c) < V_0$	2
3) $V_0 < V_t$	0

where V_t is the discriminator threshold. The discriminator output therefore gives numerical information about the input pulse amplitude sent to the analyzer.

¹⁾ A. Alberigi Quaranta and B. Righini, Nucl. Instr. and Meth. 10 (1960) 25.
²⁾ A. Alberigi Quaranta, C. Bernardini and I. F. Quercia, Nucl. Instr. and Meth. 3 (1958) 201.
³⁾ I. K. Akimov and A. S. Kusnetsov, A twenty channels pulse height analyzer (Dubna, 1959) (private communication).

The analyzer described in this paper performs this operation and also includes circuitry capable of converting the numerical information received from the discriminator so as to give an output pulse only in case¹⁾.

The whole instrument is therefore a pulse voltage amplitude single channel analyzer: the window width is equal to V_c , its lower limit being V_t . V_t and V_c are determined by the reverse bias of two distinct diodes and therefore they may be independently varied in this analyzer, which was not the case with the analyzer described in our previous paper¹⁾.

The dependence of the channel width V_c on the reverse bias of a semiconductor, instead of on passive elements as in the analyzer described in¹⁾ may seem a disadvantage: in this case, however, we have obtained the important advantage that the window width V_c may be kept constant when V_t is changed: this is, in many cases, the most convenient performance when groups of pulses must be analyzed by their amplitude standpoint.

2. The Circuit

The block diagram is shown in fig. 1 and the complete circuit in fig. 2.

The circuit operation may be described as follows: the negative input pulse to be analyzed is sent to the base of the two emitter followers T-1 and T-4; the pulse sent to T-4 is delayed by the line L-1 (delay time = 95 ns). The potentiometer at the end of L-1 matches the line to a value slightly higher than the

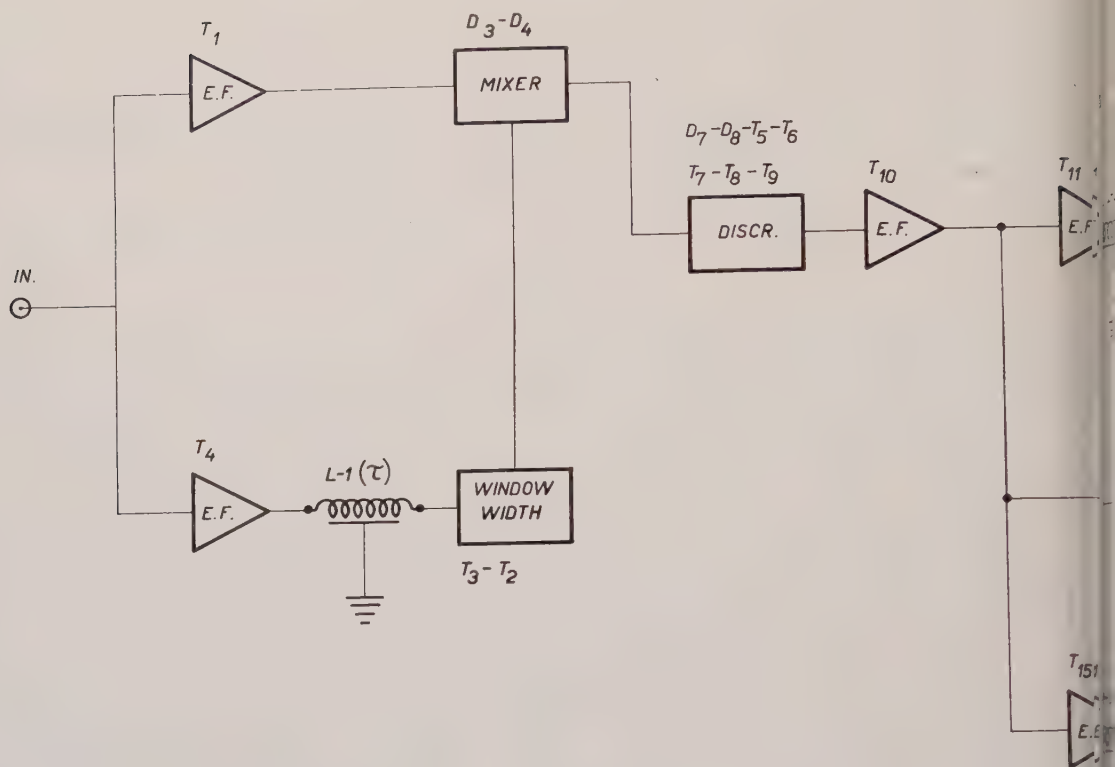


Fig. 1. Analyzer block diagram.

line characteristic impedance ($Z_0 \cong 1000 \Omega$) so as to compensate the small line pulse attenuation.

The fraction of pulse reflected because of this imperfect matching is always negligible.

The emitter follower T-3 sends the pulse to the emitter follower T-2 whose emitter, together with the cathode of diode D-4, is kept at the voltage determined by the bias of the base of T-2: this is regulated by the potentiometer P_c position.

The diode D-4 is always reversed biased: the emitter of T-1, in fact, is always kept at a voltage more negative than that of the emitter of T-2.

The diode D-3 carries therefore a current (equal to 0.72 mA), which flows, via the resistor inserted on the common anode of D-3 and D-4, to ground.

The voltage pulse on the emitter of T-2, whose amplitude is still equal to V_0 , is sent by D-4 to the common anode of D-3 and D-4; its amplitude is reduced by an amount equal to V_c , nearly equal to

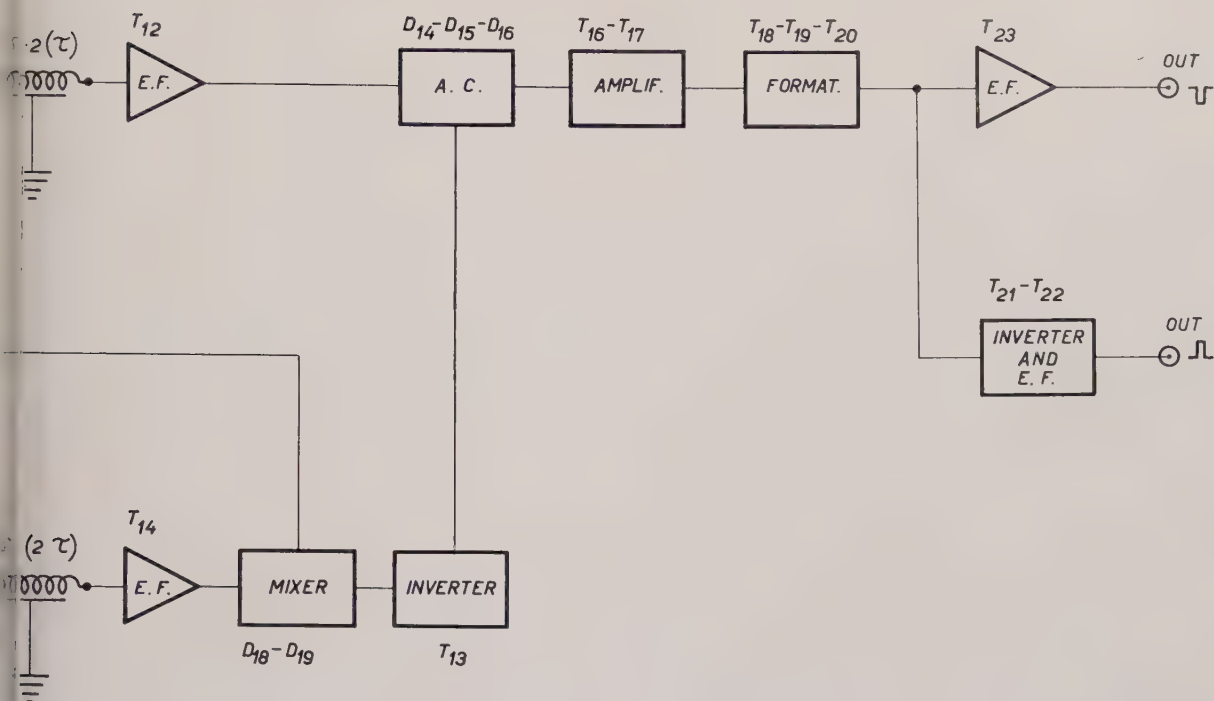
the reverse bias of D-4; this bias, as we have seen, is determined by the potentiometer P_c †.

At the common anode of D-3 and D-4, therefore, the two pulses are mixed together: the former, with an amplitude equal to V_0 , and the latter, delayed by τ , with an amplitude $(V_0 - V_c)$.

Both pulses are sent to the threshold discriminator, which is formed by the transistors T-5, T-7, T-8, T-9 and diodes D-7 and D-8.

The threshold discriminator circuit is, with some modifications, the one described by R. Gabriel *et al.*⁴). The potentiometer P_t determines the D reverse bias, as well as the threshold voltage of the discriminator.

† In a prototype of this analyzer, the potentiometer P_c has been replaced by three fixed resistors, the insertion of each of them corresponds to a determined value of the window width. In our case the three values of the window width were 0.25, 0.5, and 1 V respectively and the insertion was made by a rotary switch.



The following circuit must be capable of elaborating the information given by the threshold discriminator so as to give an output pulse when the discriminator triggers only once.

In this analyzer the circuit performing this operation is radically different from the ones described in the previous analyzers^{1,5}): its operation can be easily understood by examining fig. 3.

For the performance of this specific operation a time interval longer than the one characterizing the operation of the analyzer described in¹) is required. On the other side, this circuit, in the present analyzer is constructed using a smaller number of components and, in our opinion, its operation is more reliable.

The circuit is essentially based on the anti-coincidence circuit formed by the diodes D-14, D-15 and D-16. The pulse coming from the threshold discriminator is delayed by the line L-2, formed by L-4 and sent, via the emitter follower T-12, to the anticoincidence. The anticoincidence veto input, on the contrary, is fed by pulse trains obtained by the same undelayed pulse given by the discriminator: to each of them a pulse delayed by 2τ is added.

This part of the circuit is formed by the emitter followers T-15 and T-14, the delay cable L-3 (delay time = 2τ), the mixer D-18, D-19 and the inverter T-13.

As seen by fig. 3, only in case 1 is there a negative pulse which is required to fire the normally cut-off transistor T-16. In this case the univibrator T-18, T-19 gives a pulse of constant form: this pulse is sent both to the emitter follower T-23 (negative output) and to T-21 and T-22 (positive output).

⁴) R. Gabriel, E. L. Garwin and C. M. York, Nucl. Instr. and Meth. **5** (1959) 247.

⁵) A. Alberigi Quaranta, C. Bernardini, C. Infante and I. F. Mercia, Nucl. Instr. and Meth. **5** (1959) 120.

0.5 cm and wired as directly as possible to reduce to a minimum their capacitance and inductance. The supply voltage is -18 V and the current is 1 mA.

Performance

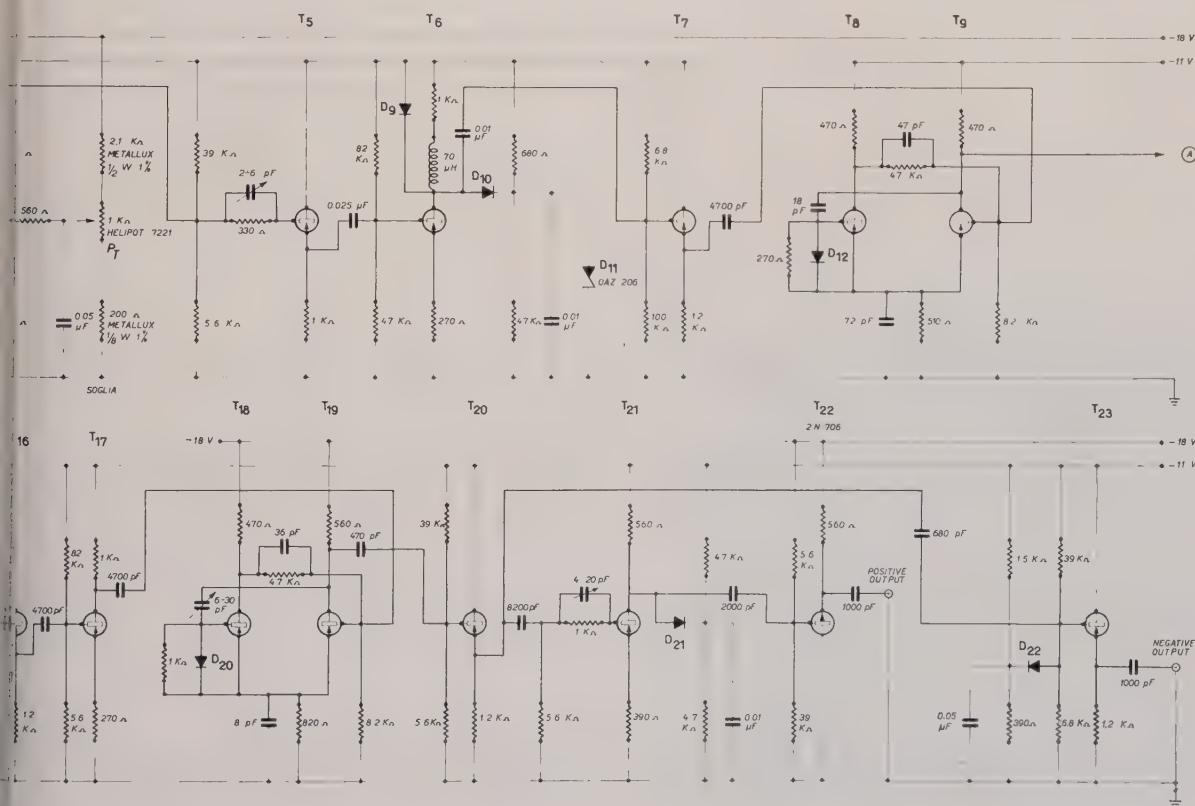
A great many tests have been carried on a prototype of the analyzer in order to find out its performance; the prototype has been continuously in operation for about 700 hours, during which most of the tests were made, without any trouble. The results are given herewith: to verify the analyzer behaviour at high repetition rates, the calibration curves were determined for various frequencies ranging from few cycles per second up to 2 Mc/s and for three different values of the window width: the input pulses were 25 ns wide; their rise time was 1.5 ns (figs. 5, 6, 7).

In these diagrams E_H and E_L indicate the upper and lower limits of the channel.

The calibration curves have been drawn by varying the amplitude V_0 of the pulses to be analyzed versus the potentiometer P_T position for three different positions of P_c ; these positions correspond, respectively, to three different amplitude intervals to be analyzed (window width), equal to 0.25, 0.5 and 1 V.

From these curves it is evident that the amplitude of the input pulses may be changed in the range $0.3 \div 5.8\text{ V}$, corresponding to the lower and upper limits of E_L and E_H respectively.

The lowest values of E_L depends mainly on the minimum pulse amplitude required to trigger the threshold discriminator (0.21 V); the highest value of E_H is chiefly determined by the maximum admissible reverse bias of D-7, equal to -6 V .



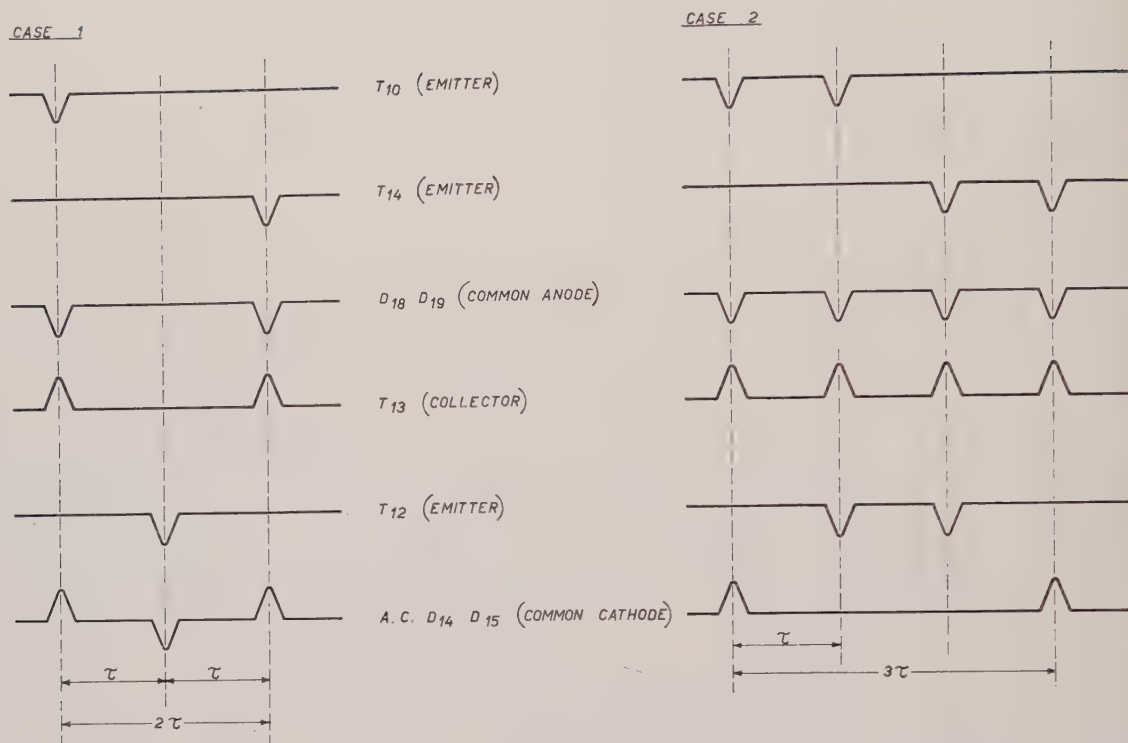


Fig. 3. Analyzer operation: pulses in various points of the circuit for the two possible cases.

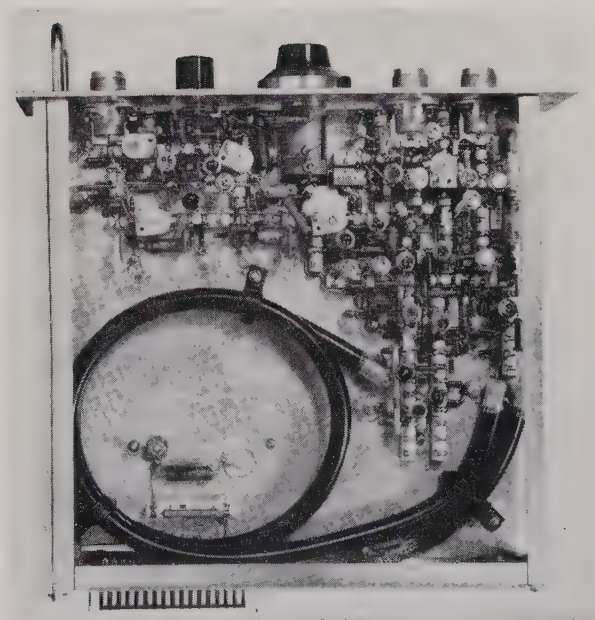


Fig. 4. Photograph of the apparatus.

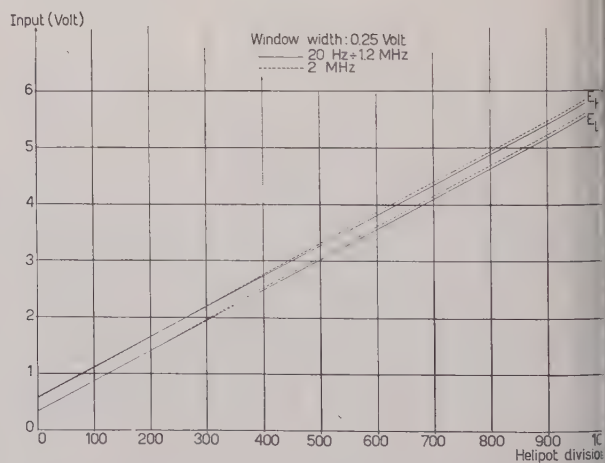


Fig. 5. Calibration curves for a 0.25 V window width.

figs. 5, 6 and 7 are drawn and compared, for the value of the window width, the calibration curves obtained in the above mentioned range of input pulse repetition rates.

From these curves it may be seen that, when the input pulse repetition rate varies within 20 c/s and 2 Mc/s, the threshold is constant when the input

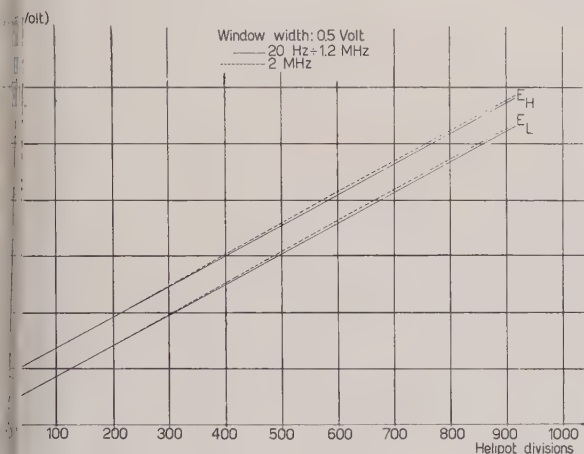


Fig. 6. Calibration curves for a 0.50 V window width.

frequency varies within 20 c/s and 1.2 Mc/s; higher frequencies, on the contrary, the threshold is subject to sensible variations that, at a frequency of 2 Mc/s, are of the order of 2% as clearly shown in the diagrams.

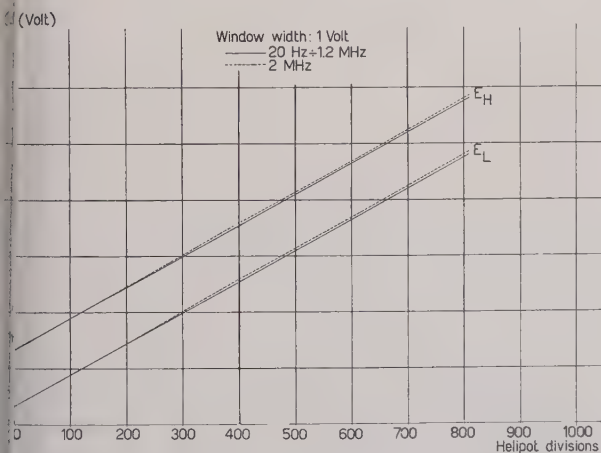


Fig. 7. Calibration curves for a 1 V window width.

It must be noted that to obtain experimentally the above mentioned curves, the input, pulse amplitude V_0 was measured by an oscilloscope by which

the best possible accuracy was of the order of some percent of the amplitude to be determined.

In addition, tests of this type, carried on different conditions of room temperature, showed no change in the circuit performance when the temperature was varied between 10°C and 40°C.

Therefore we can conclude that the threshold does not sensibly change when the input pulse frequency varies from low frequencies to 1.2 Mc/s; for higher frequencies there is a threshold change, that, for a frequency of 2 Mc/s, is of the order of 2%.

The window width, on the contrary, does not vary when the input pulse repetition rate is changed in the above mentioned frequency interval.

Tests have been carried on to verify a possible influence of the input pulse width (T) on the analyzer behaviour.

The measurement showed that T may be changed from 20 ns to 70 ns without sensibly altering the analyzer calibration curves. These tests were carried on by a SELO GI/41 Hg-relais pulse generator ($T_R = 5 \times 10^{-10}$ s, $f_{max} = 100$ c/s), as the pulse generator used to obtain the previous mentioned calibration curves could not give pulses wider than 30 ns.

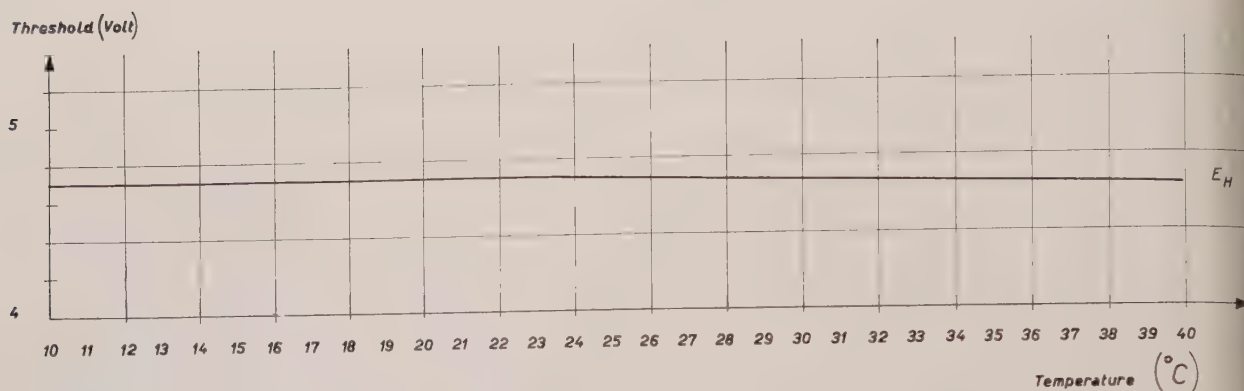
To obtain more detailed and accurate information about a probable dependence of the threshold and channel on temperature variations, we used as pulse source the above mentioned Hg pulse generator.

In order to obtain a higher accuracy in the determinations of the pulse voltage amplitude and a good amplitude reproducibility we purposely modified this instrument.

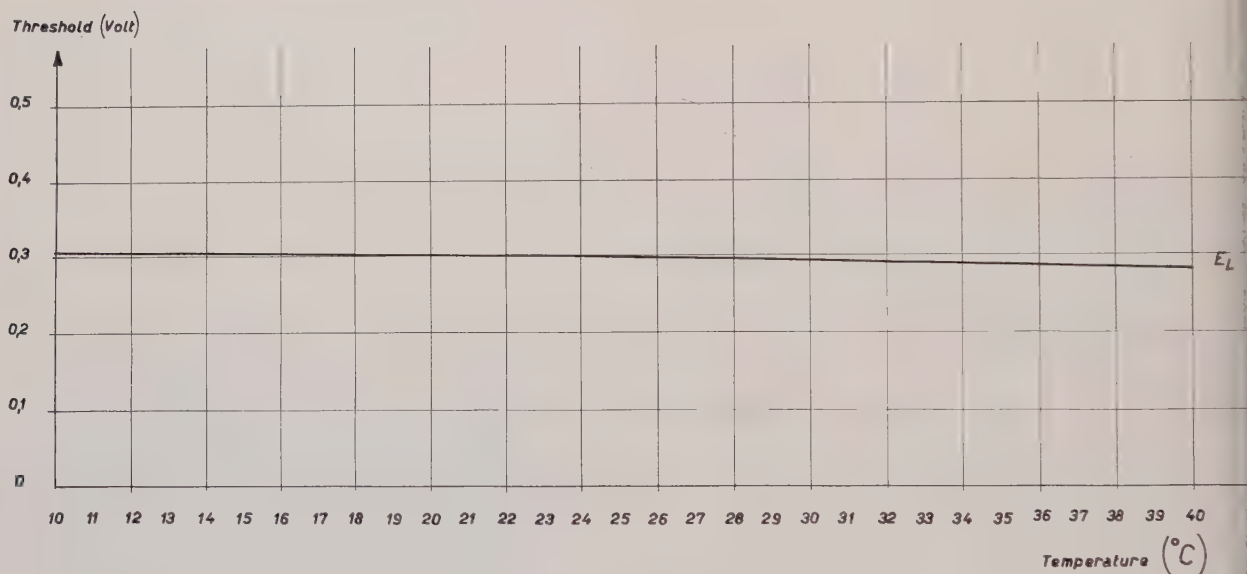
In particular, the d.c. voltage charging the piece of the pulse forming line was continuously tested by a potentiometric method.

By this way we were able to read the pulse amplitudes in the desired range of 0.3 ÷ 6 V with an accuracy of 1‰.

In fig. 8 is given the dependence of the threshold on room temperature for two values of it: it may be seen that the variations are kept within a 5% for the threshold of the lower value (300 mV); for the 4.7 V threshold there was no observable change when the temperature varied from 10°C to 25°C, while there was a change of the order of 1.5% in the range 25°C ÷ 40°C.



(a)



(b)

Fig. 8. Behaviour of the threshold against temperature variations; (a) 4.7 V threshold, (b) 0.3 V threshold.

In fig. 9 is represented the behaviour of a 1 V channel on temperature variations within 10°C and 40°C.

It may be seen that the window width is practically constant when the temperature is changed from 10°C to 27°C, whereas there is a channel change of about 1.4% when temperature is changed from 27°C to 40°C.

From this series of tests we can conclude that the threshold changes for room temperature ranging from 10°C to 40°C are of the order of 1%; the corresponding channel change is less than 1.5%.

Threshold and channel drift has been also determined for a time interval of 240 hours; the result was of the order of 1% for the threshold; the channel showed no appreciable change.

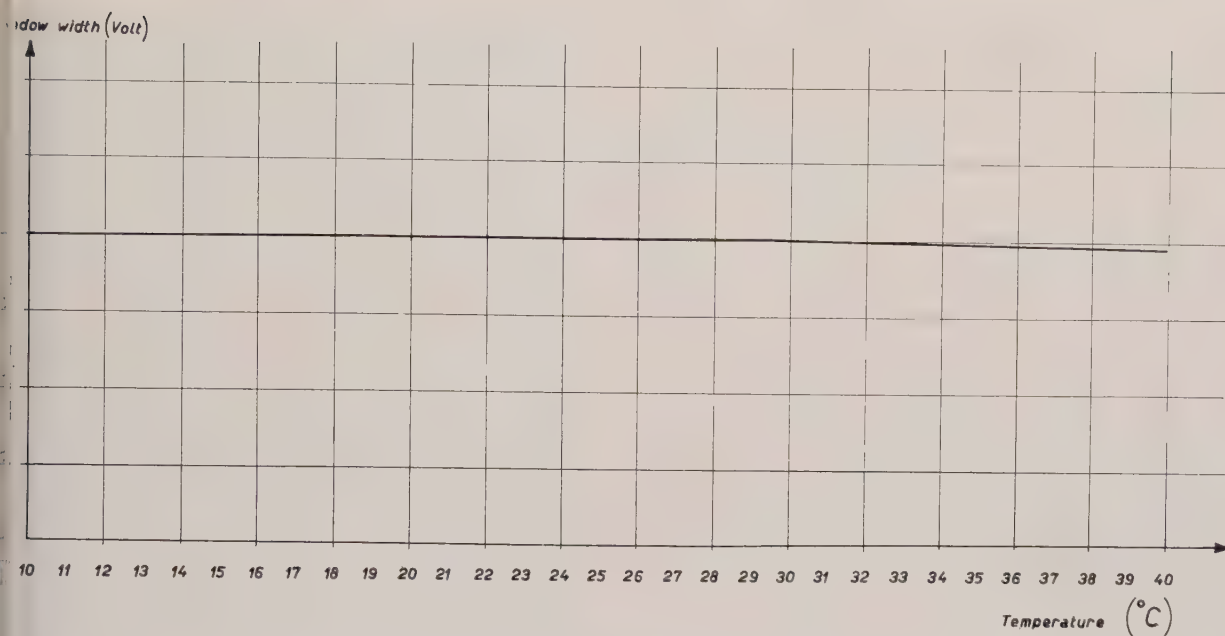


Fig. 9. Channel behaviour against temperature variations.

The narrowest separation between two input pulses correctly analyzed depend also on τ ; in our case τ was 95 ns and the total dead time was about 190 ns.

Tests were carried on to determine the delay between input and output and its probable variations when the amplitude V_0 of the input pulse was changed in the interval whose limits are E_L and E_H . The result of this measure was that the delay

variations, tested for several input pulse widths and at the extreme limits of the calibration curves, are kept within ± 10 ns with respect to the average value that the delay has at the center of the same curves (151 ns).

We wish to thank Mr. R. Volta for his precious contribution in wiring and testing the circuit and for some useful suggestions.

A BEAM PROFILE INDICATOR FOR USE WITH HIGH ENERGY PARTICLE ACCELERATORS

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A.E.R.E., Harwell, Didcot, Berks.

Received 28 August 1961

The equipment described enables the rate of high energy particles passing through a 5" by 5" array of plastic scintillators to be displayed directly as an analogue pattern on the screen of an oscilloscope. The pattern is a 10 by 10 array of 100 spots on the cathode ray tube, the intensity of the spots representing the particle intensity through the corresponding $\frac{1}{4}$ " $\times$ $\frac{1}{2}$ " element of the detector. Provision is also made for the direct

storage of the counts from the 100 elements in the memory of a suitable 100 channel pulse height analyser. The unit can be gated with an external counter enabling some other criterion to be demanded of the particles recorded. Tests made on the unit indicate that it is possible to use it to display directly and record the profile of beams of high energy particles in the intensity range of one per second to $\sim 10^6$ per second.

1. Introduction

A general problem that exists for most high energy accelerators is one of transporting beams of particles over considerable distances. In order to do this it is normal to set up complex transport systems involving magnetic quadrupole lenses, bending magnets and sometimes velocity separators. In setting up these transport systems and optimising the numerous parameters it is of considerable advantage to be able to view the beam profile at some relevant point in the transport system while actually adjusting the available beam transport parameters. If the beam intensity is high (greater than 10^7 /sec) this can be achieved by placing a scintillating material in the beam and viewing it with a closed circuit television system.

For low intensity beams, or beams in which the particles one is interested in are accompanied by a considerable background of other particles, no simple solution is available and the unit described below has been constructed to fill this gap. Its performance under test indicates that it fulfils the requirements for beam intensities of one particle per second to intensities of $\sim 10^6$ particles per second.

2. Description of the Beam Profile Indicator and Associated Circuitry

The detector consists of a matrix of plastic scintillators of overall area 5" by 5" which is placed in the beam. This matrix is made up of twenty 5" $\times$ $\frac{1}{2}$ " strips of $\frac{1}{4}$ " thick NE 102 plastic scintillator and

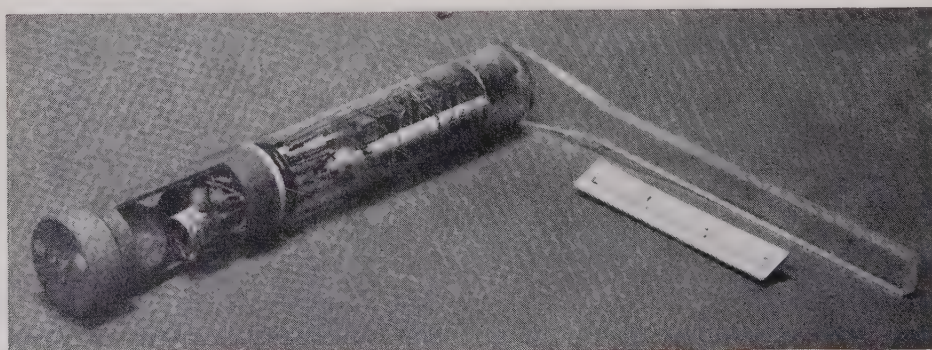


Fig. 1. This photograph shows one of the 5" $\times$ $\frac{1}{2}$ " strips of $\frac{1}{4}$ " thick NE 102 plastic scintillator with its light pipe and phototube complete with base.

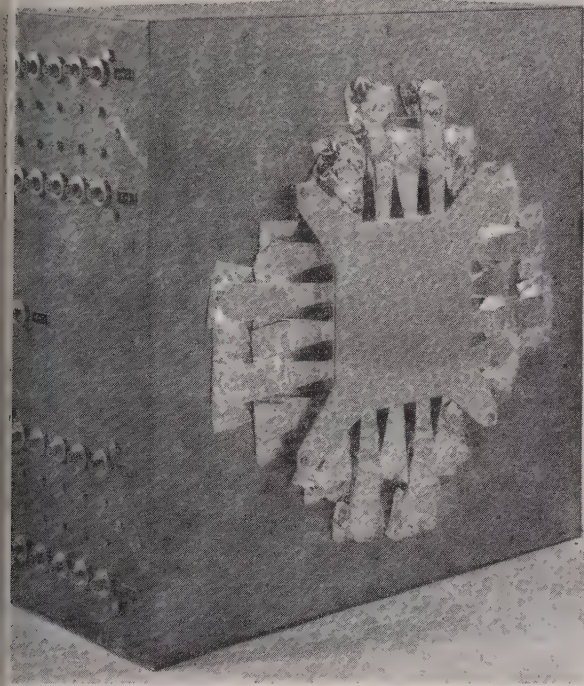


Fig. 2. This photograph shows the front view of the matrix detector with its lid removed. The twenty light pipes which are wrapped in aluminium foil can be seen.

anged in two sets of ten parallel strips forming two $5'' \times 5''$ planes behind each other. The strips in the two planes are orthogonal, one set being labelled x_1 to x_{10} and the other y_1 to y_{10} . The beam passes through these two planes, each particle traversing one of the twenty strips. The strips of scintillator are individually wrapped in aluminium foil, to stop light escaping into the neighbouring strips, and are viewed by twenty 9524 B E.M.I. photomultiplier tubes, see fig. 1, 2 and 3. The output from these phototubes is fed to transistor circuitry which is designed to reproduce either an analogue display on an oscilloscope, or a digital record stored in the memory of a suitable 100 channel pulse height analyser.

Fig. 1, 2 and 3 show the construction of the detector assembly. Perspex light pipes are arranged to transmit the light from the twenty strips of scintillator to the twenty phototubes. The tubes are mounted in light-tight brass tubes and are magnetically shielded by μ -metal sleeves on the outside of these brass tubes and by a μ -metal outer

box. The overall size of the box is $13'' \times 13'' \times 8''$. The material in the beam over the $5'' \times 5''$ sensitive area is $\frac{1}{16}''$ of brass, $\frac{1}{16}''$ aluminium and $\frac{1}{2}''$ of plastic scintillator.

The twenty 9524 B phototubes are run from a single E.H.T. supply set to about 1.8 kV, the total current drawn being ~ 5 mA. The phototubes are not selected and the voltage on the individual tubes is adjusted, by means of $1\text{ M}\Omega$ variable resistors in series with each resistor chain, to give 0.1–0.15 V into 100Ω for the passage of minimum ionizing particles through the matrix.

Fig. 4 is a block diagram of the associated circuitry as used with an oscilloscope display using a Tektronix 545 oscilloscope. The pulses from the phototubes are fed into discriminators which produce standard output pulses and reject the noise from the phototubes. These standard pulses are fed through suitable attenuators; $\frac{1}{10}$ for x_1 and y_1 , $\frac{2}{10}$ for x_2 and y_2 etc., and the x outputs are connected to the x amplifier of the oscilloscope, and the y outputs to the y amplifier. The output pulses from the discriminators are ~ 500 nsec at half height and have ~ 400 nsec flat top. The delays in the system are adjusted so that the spot on the oscilloscope screen remains stationary during the

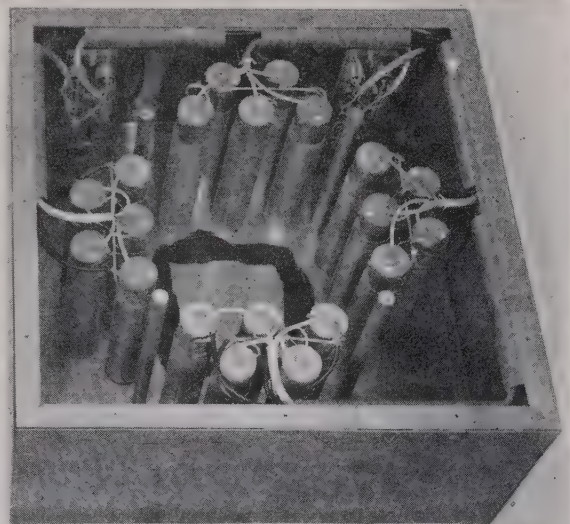
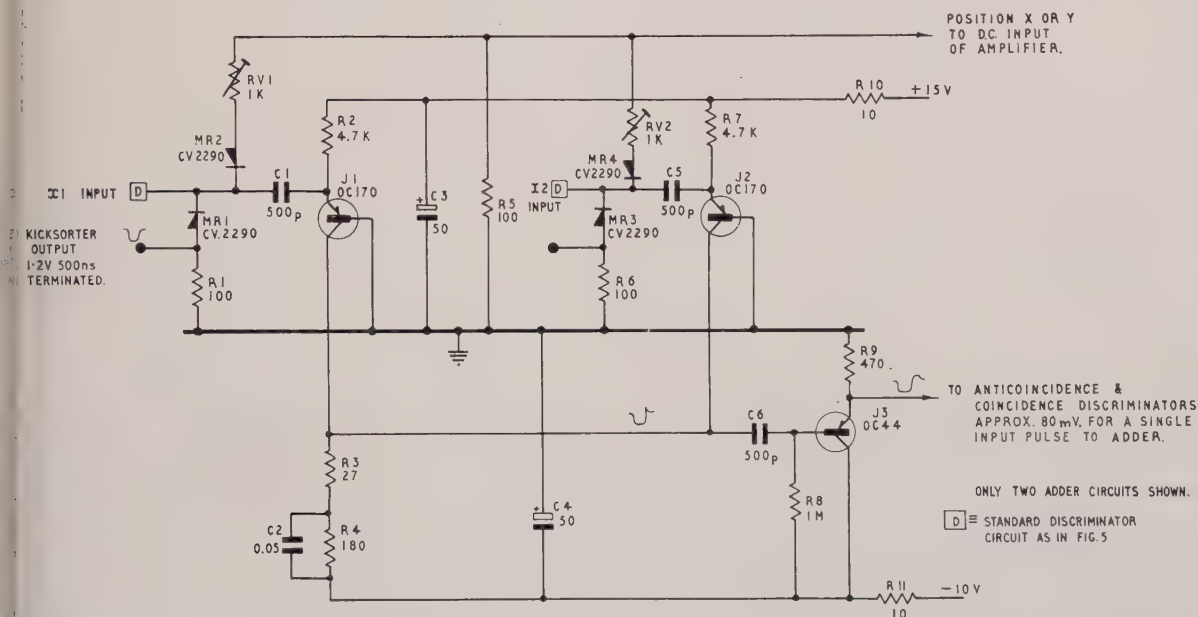


Fig. 3. This photograph of the back of the detector shows the twenty phototubes in position. The μ metal screening sleeves can be seen. The outer box has μ metal sides as further magnetic screening.

an alternative method of recording the information is to store each event in the memory of a suitable 100 channel pulse height analyser. The outputs of the x and y discriminators can be fed to the x y address system of the memory and the

One of the discriminators receiving the output

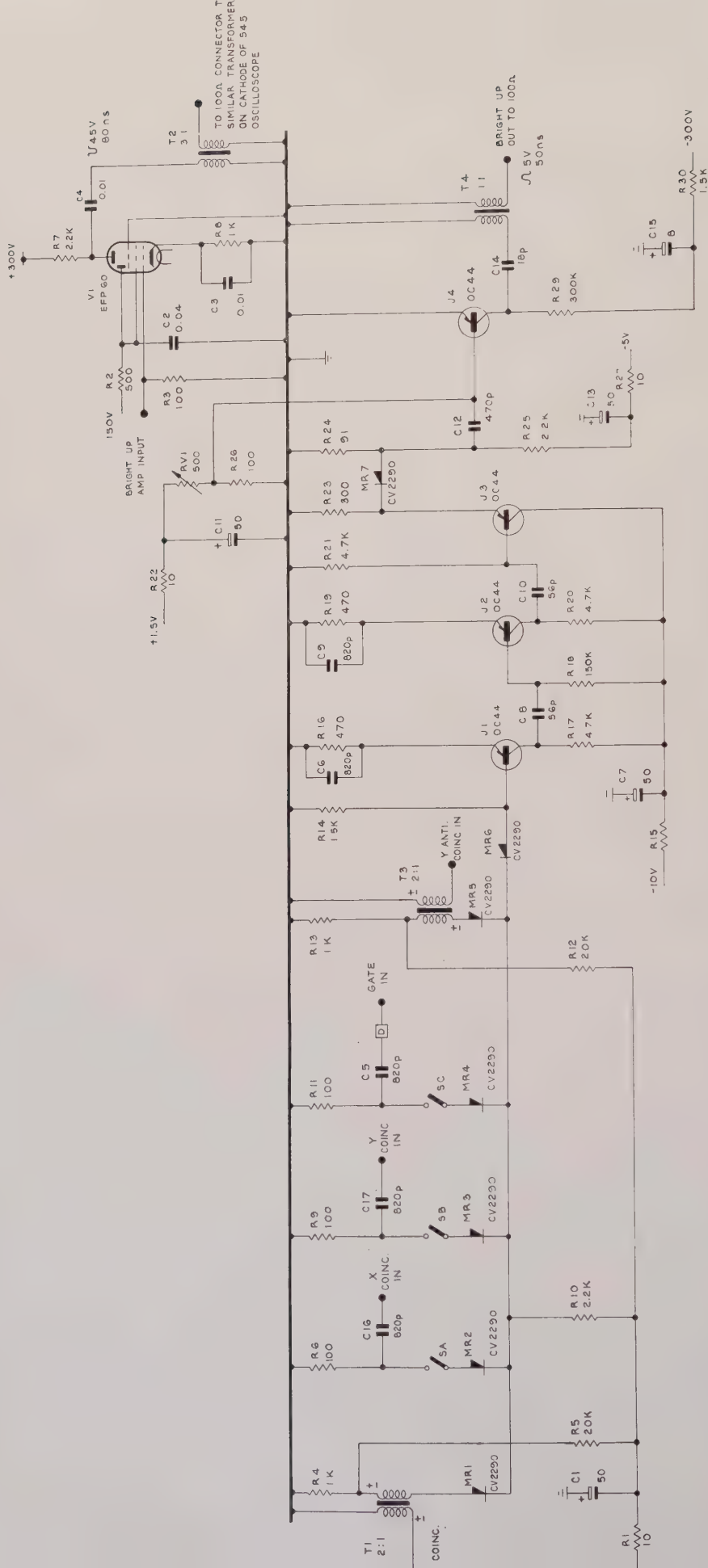


6. Circuit diagram of the pulse adder showing the output circuitry for the analogue display and for the digital storage.

The discriminators used are a modification of a circuit, see fig. 5, designed by J. G. Page of the Electronics Division, Harwell. The twenty discriminators receiving pulses from the phototubes are set to trigger with negative pulses of 60 mV or greater. The output pulses are $\frac{1}{2}$ μ sec negative square pulses of 2.5 V amplitude when fed into 50 Ω .

pulse from the adder is set to trigger at ~ 50 mV, its output is differentiated to shorten the pulse to ~ 200 nsec and it is fed into a coincidence input of the coincidence unit. The other discriminator is set to trigger at ~ 120 mV (i.e. to trigger when two or more of the x scintillators are traversed by a particle) and its output is fed into an anti-coincidence channel. Identical circuits are used for the γ detectors.

The coincidence unit, see fig. 7, is a conventional diode circuit using CV 2290 diodes with a common cathode load. The 2.5 V negative 200 nsec pulses from the coincidence discriminators cut the diodes off and the resulting pulse from the common cathode load is amplified and fed through a biased diode (to reject small pulses from capacitive feed through) onto the base of an OC 44 in an avalanche circuit.



□ ≡ STANDARD DISCRIMINATOR CIRCUIT
AS IN FIG 5.

Fig. 7. Circuit diagram of the coincidence unit and the "bright up" pulse amplifier.

The anti-coincidence circuits use pulse transformers to invert the negative input pulses, the

This test generator can be used quickly to test the circuit and is used to set the display on the oscilloscope. A perspex mask with a 10×10 grid scribed on it is fitted over the oscilloscope screen. The oscilloscope gains and position controls are adjusted to position the $x_1 y_1$ spot and the $x_{10} y_{10}$

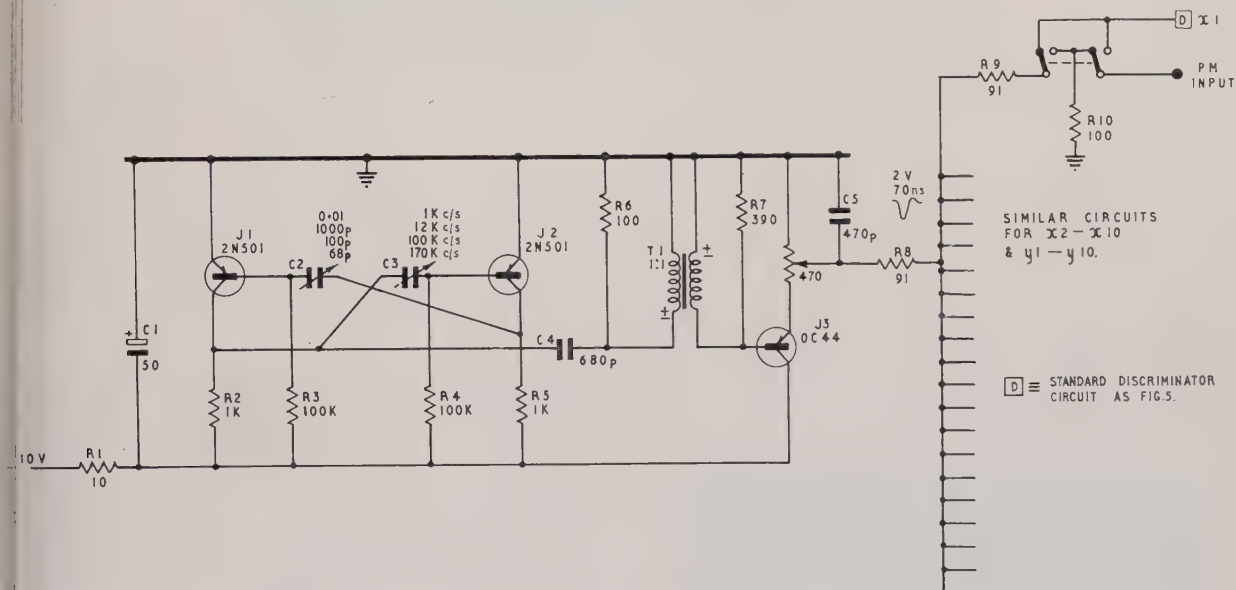


Fig. 8. Pulse generator for testing circuit. The output from the test generator can be switched into any of the twenty input circuits.

To aid in setting up the unit, a pulse generator as built which can provide 100 mV, 50 nsec negative pulses to any of the twenty input discriminators, see fig. 8. Switches are provided to connect these pulses into any number of the discriminators. The pulse generator is a multivibrator using two 2N 501 transistors. The output is differentiated and fed out through an OC 44 in the grounded collector configuration. The output amplitude can be ad-

spots in the correct squares of this grid. The other combinations automatically follow after the initial setting of the attenuators.

3. Performance of the Unit

The unit has been tested at low counting rates using cosmic-ray muons and at high counting rates using a beam of 151 MeV protons. The former tests were made with an overall counting rate of about one per second and verified that one can observe on the oscilloscope the single spots corresponding to the passage of single particles through the matrix. However, a better overall impression of the profile is obtained with these very low counting rates by integrating the display for a few minutes by photographing the oscilloscope screen with a polaroid

camera. No difficulty was experienced in using the matrix at these low counting rates either with or without external gating.

placed behind the matrix. Fig. 10 shows the gated and ungated displays.

Tests were made using different beam intensities

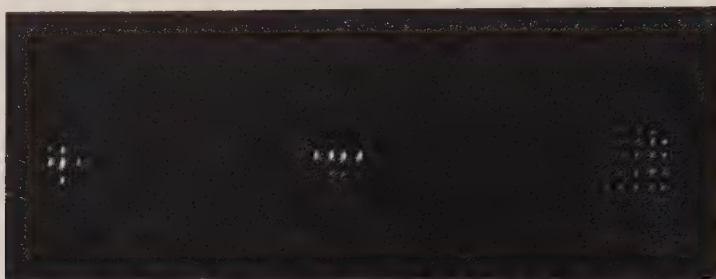


Fig. 9. A photograph of the oscilloscope display for tests made with a 151 MeV proton beam. The beam profile for 3 different settings of the focusing quadrupoles in the beam transport system are shown.

The tests made at higher counting rates were made by placing the matrix in the proton beam from the Harwell cyclotron in one of the normal target positions.

The beam intensity was reduced to an average rate of $\sim 10^3/\text{sec}$ which is equivalent to an instantaneous rate of $\sim 10^5/\text{sec}$ as the duty cycle was about 1%. Quadrupole focusing magnets and

and it was found that a reasonable display could be obtained for instantaneous intensities up to $\sim 10^6/\text{sec}$, although at this counting rate there were considerable losses as the overall dead time of the circuits is $2 \mu\text{sec}$.

No tests have as yet been made on the storage of the information in the memory of a 100 channel pulse height analyser.

4. Conclusions

The unit has worked successfully for input counting rates of from $1/\text{sec}$ to $\sim 10^6/\text{sec}$ and should be of considerable use in setting up transport systems for beams of high energy particles, especially for low intensity beams.

One useful application will be studying the profile of a low intensity beam of required particles in a background of contaminating particles. It will be possible to gate the unit with a detector chosen to accept the required particles and reject contaminating particles.

Acknowledgements

It is a pleasure to acknowledge the encouragement and guidance of Dr. W. Galbraith throughout this work, Dr. E. Bretscher for his interest in it and the assistance we have obtained at all stages from Mr. J. G. Page and other members of the Electronics Division of A.E.R.E. We are grateful to Mr. B. Rose and other members of the Cyclotron Group, A.E.R.E. for their collaboration.

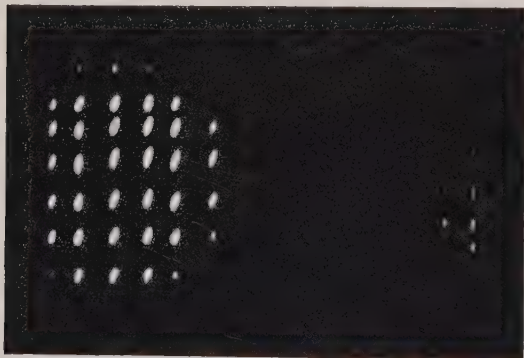


Fig. 10. A photograph of the oscilloscope display for tests made with a 151 MeV proton beam. The left photograph shows the full beam. The right photograph shows the display obtained with the same beam by gating the matrix with a small counter placed immediately behind the matrix.

steering magnets were available to focus and deflect the beam. The beam display was watched while the magnet controls were used to steer and focus the beam. Fig. 9 shows the beam display for three different settings of the quadrupoles. The gated operation of the matrix was demonstrated by gating the unfocused beam with a small counter

DESIGN AND USE OF A SELF-MONITORING COINCIDENCE ARRANGEMENT OF NANOSECOND RESOLUTION

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A self-monitoring coincidence arrangement of delayed coincidences is described. The resolving time of the coincidence system is 2 ns. The half-lives for the 1.07 MeV first excited state of Sr^{86}

and 1.52 MeV first excited state of Ca^{42} are determined to be < 0.1 ns and (1.0 ± 0.4) ns respectively by this delayed coincidence method.

1. Introduction

In determining the half-lives of excited states of nuclei by the delayed coincidence method one looks for the coincidence events as a function of the channel delay between the gamma-quanta (or the internal conversion electrons) emitted from the nucleus of the excited state and some point on the beta-ray energy continuum. Such coincidence observation is made first using a prompt radiation source and then the delayed source under investigation. The two main points which are of special importance for the success of the above method are (a) selection of proper radiations for the two detectors in such a manner that the unwanted radiations may be avoided and (b) working of the two detectors under similar energy conditions in the prompt and delayed experiments such that the two detectors have the same response time in the two cases. The above two conditions can be accurately satisfied by using beta-ray magnetic spectrometers. Its use allows one to select the desired radiations free of interference from unwanted radiations of different comparable lifetimes. This freedom from interferences is specially important when the short lifetimes are to be measured. Coincidences caused by radiations scattered between the two counters can easily be avoided by this device.

After selection through the spectrometers coincidences are measured between the nuclear beta-rays and the conversion electrons. Suitable prompt and

the delayed sources are chosen such that the proper beta energy equal to the conversion electron energy can be selected out from the nuclear beta-ray continuum thus satisfying the condition (b) above.

Another method is to approximately satisfy the above conditions by using the organic scintillation detectors and a fast and slow coincidence arrangement. The energy selection is done in the two slow channels. Here it is difficult to avoid unwanted radiations of comparable energies and of approximately the same lifetime as under investigation. Moreover the energy condition can only be satisfied approximately, since selection of narrow energy windows on the slow channels causes the coincidence rate to be reduced by a large factor, which is undesirable.

We describe below a post-coincidence arrangement. It incorporates a comparatively slow monitoring circuit which works under identical conditions as the fast coincidence circuit and records the total number of coincidence events C from the source taking place in the same period as of the fast coincidences C_1 . Division of C_1 by C makes this ratio independent of the counting efficiency of the detectors. In addition, in our arrangement there is no drift in the coincidence counting efficiency, since the limiting of pulses is not used.

2. The Post-Coincidence Technique

Attempt has been made by us to develop a post-coincidence arrangement on the principle outlined

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by Bay¹) (Trans. IRE Nov. 1956). The coincidence arrangement is shown in fig. 1. It utilizes three coincidence circuits (resolving times ~ 0.7 ns, ~ 5.4 ns, and $0.6 \mu\text{sec}$) which have been designed

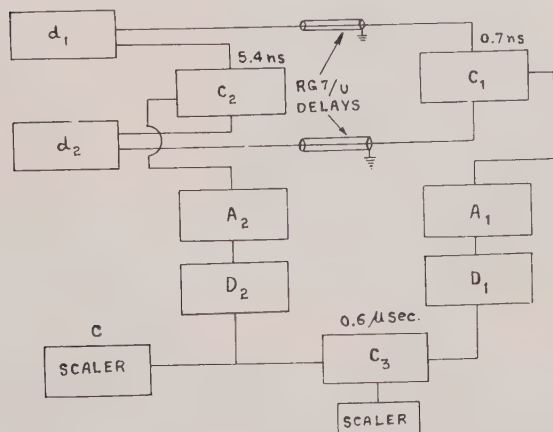


Fig. 1. Block diagram of the post-coincidence arrangement.

and fully worked out. Trans-stilbene scintillators and RCA-5819 photomultipliers (d_1 and d_2) have been used to provide input pulses for the coincidence circuits. A cobalt-60 source has been used as a prompt source of radiations. Negative anode pulses are fed to a germanium diode bridge fast coincidence circuit C_1 (refs.^{2,3}). The resolving time of the circuit using shorted coaxial cable technique is ~ 0.7 ns. The positive 10th dynode pulses are fed to a similar diode coincidence circuit C_2 used without shorted input stubs to give a resolving time ~ 5.4 ns. This slow circuit gives the total number of coincidences, whereas there is some loss in coincidences from the faster circuit C_1 because of its short resolving time. The coincidence outputs from these two circuits are amplified (Atomic's 204B) and after amplitude discrimination are fed to a Rossi type coincidence circuit C_3 of resolving time $0.6 \mu\text{sec}$ at 100% coincidence detection efficiency. The final coincidences from this circuit and the total coincidence counting rate C from the circuit C_2 can be simultaneously recorded over two scalars. Introduction of variable time delays in terms of various RG7/U cable lengths (characteristic impedance 100 ohm) in the input channels of the fast coincidence circuit C_1 gives the fast coincidence resolution curve. This post-coincidence ar-

angement has the following main advantages:

- (i) stability and simplicity,
- (ii) no correction is needed for the decay in strength of a radioactive source during experiment,
- (iii) no correction is to be applied for the change in solid angles which may be of importance in certain applications.

The concept of the quantity called the total coincidence counting rate C of the experiment is of importance. The circuit C_2 gives this quantity. In addition, the circuit C_2 monitors the post-coincidence arrangement against any temporal fluctuations.

The quantity C is recorded simultaneously with the final coincidences in the prompt and the delayed experiments. By dividing the final output coincidence rate by C in each observation the effect of any fluctuations in the source strength as under (i) and (iii) above is thus taken into account. The prompt and the delayed coincidence rates plotted versus negative and positive time delays gives the

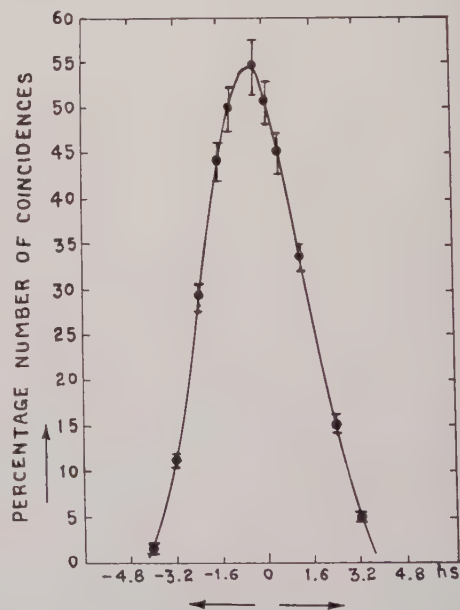


Fig. 2. Ni^{60} gamma-gamma reduced coincidence resolution curve.

¹ Z. Bay., IRE Trans. on Nuclear Science, (Nov. 1956) p. 1.

² N. K. Saha and S. C. Pancholi, Proc. NIS India 26 (1960) 464.

³ S. C. Pancholi and N. K. Saha, Proc. NIS India 27 (1961) 155.

reduced coincidence resolution curves which are normalised in area.

A cobalt-60 gamma source was used as a prompt source of radiations (gamma quantum energies 1.33 and 1.17 MeV) for producing gamma-gamma coincidences. The final coincidence counting rate and the total coincidence rate C were recorded simultaneously over two scalers for each observation. Fig. 2 shows the reduced coincidence resolution curve. The x -axis shows the negative and positive time delays introduced in the channels and the ordinate gives the percentage number of the reduced coincidences (obtained on dividing the final coincidence rate by C , the total coincidence rate). We observe from this curve the reduced coincidence resolution time. The curve gives a resolving time of ~ 2 ns for this post-coincidence arrangement.

Application of the Method

As a test of the post-coincidence arrangement we determined the half-life of the 1.29 MeV excited state of W^{182} . The value obtained by us was in agreement with that of Sunyar⁴) within our errors of observations.

UPPER LIMIT OF THE HALFLIFE OF THE 1.07 MeV EXCITED STATE OF Sr^{86}

In the experimental measurement of half-life of the 1.07 MeV excited state of Sr^{86} has not yet been reported in the literature. The measurement of this half-life was carried out on the post-coincidence arrangement described above. A $40 \mu c$ Rb^{86} source was sandwiched between two thin trans-stilbene scintillators backed by RCA-5819 photomultipliers. The left counter was made for beta's and in front of the right side scintillator a 500 mg/cm^2 Al shield was placed to cut-off all beta's (max. energy 0.71 MeV), so that gamma's (energy 1.07 MeV) from the daughter nuclei Sr^{86} only reach it. The circuit adjustments were done as mentioned earlier and the number of beta-gamma coincidences was observed before and after the introduction of negative and positive time delays in C_1 coincidence channels. The total coincidence counting rate C was also observed simultaneously from C_2 on a separate scaler for each time delay introduced.

Next, the delayed radiation source Rb^{86} was

replaced by a cobalt-60 ($\sim 50 \mu c$) prompt source and the above method was repeated observing now gamma-gamma coincidences. In both the cases a number of sets of observations was taken and their

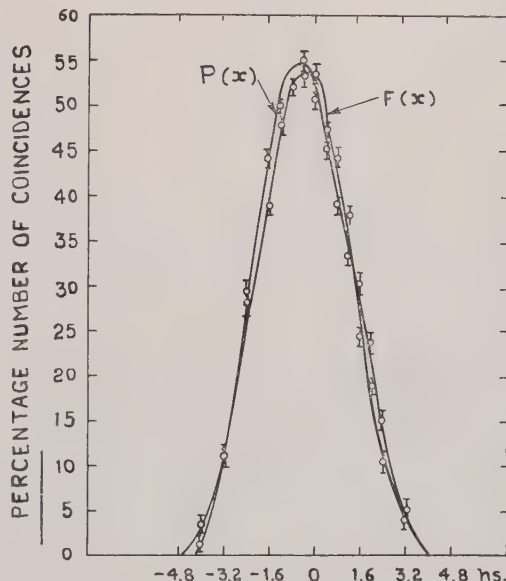


Fig. 3. Ni^{60} prompt gamma-gamma reduced coincidence curve $P(x)$ and the delayed Sr^{86} beta-gamma reduced coincidence curve $F(x)$.

mean curves were plotted which are shown in fig. 3. The ordinate for each point has been obtained by dividing the final coincidence rate by C , the total coincidence rate. The two curves (prompt $P(x)$ and delayed $F(x)$) are almost overlapping, but there is a clear shift of the delayed curve $F(x)$ to the right. From an analysis of these curves we estimate the half-life of the 1.07 MeV excited state of the daughter nucleus Sr^{86} as < 0.1 ns. The Weisskopf estimate gives a value 0.017 ns.

3.2. HALFLIFE OF THE 1.52 MeV EXCITED STATE OF Ca^{42}

No previous experimental determination of half-life for the first excited state of Ca^{42} seems to exist.

Following exactly the experimental procedure given above, we obtained the prompt reduced coincidence curve $P(x)$ for Ni^{60} gamma-gamma coin-

⁴) A. W. Sunyar, Phys. Rev. **93** (1954) 1122.

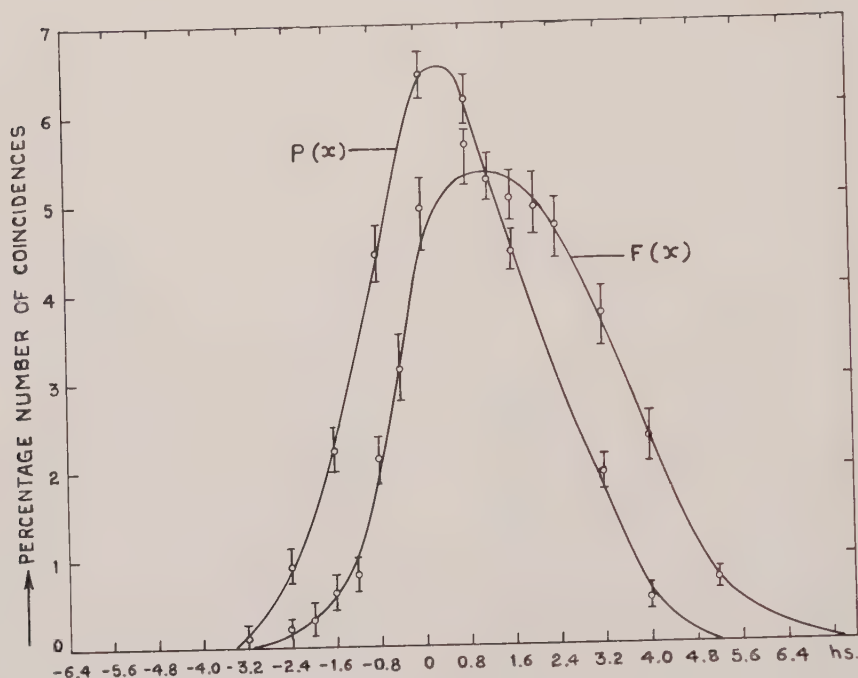


Fig. 4. The beta-gamma delayed reduced coincidence curve $F(x)$ obtained from the 1.52 MeV gamma-rays of Ca^{42} , and gamma-gamma prompt reduced coincidence curve $P(x)$.

cidences, and the delayed reduced coincidence curve $F(x)$ for Ca^{42} beta-gamma coincidences. The strength of the parent K^{42} source was $40 \mu\text{C}$. The results for the mean of two runs each for the prompt and the delayed sources are shown in fig. 4. Again the right side of the delayed curve $F(x)$ corresponds to beta counts channel. The $F(x)$ curve is shifted appreciably to the right of the prompt curve $P(x)$. Furthermore, the $P(x)$ and the $F(x)$ curves start approximately from the same point on the left and the maximum of the delayed curve lies on the prompt curve. An analysis of the curves by Newton's area method⁵ gave a value (1.0 ± 0.4) ns for the half-life of the 1.52 MeV excited state of Ca^{42} . The Weisskopf estimate gives a value of 0.011 ns for this state.

4. Results

1.07 MeV excited state of Sr^{86}

$$T_{\frac{1}{2}} < 0.1 \text{ ns}$$

and

1.52 MeV excited state of Ca^{42}

$$T_{\frac{1}{2}} = (1.0 \pm 0.4) \text{ ns}.$$

Acknowledgements

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⁵ T. D. Newton, Phys. Rev. **78** (1950) 490.

ANALYSIS OF GAMMA-RAY SCINTILLATION SPECTRA BY THE METHOD OF LEAST SQUARES

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The method of least squares has been applied to the analysis of gamma-ray scintillation spectra, the calculations being performed on a Ferranti "Mercury" computer. The method is superior to the usual graphical methods of quantitative inter-

pretation. Analytical results are obtained rapidly, the accuracy being consistent with the calculated precision. The method is particularly suitable for routine analysis at low counting rates.

Introduction

Scintillation gamma-ray spectrometry has proved a useful tool both in the identification of radionuclides and their quantitative assessment. However, such quantitative measurements are subject to uncertainties due not only to the statistical nature of radioactive disintegration but to difficulties in resolving exactly that part of the spectrum to be measured.

The simplest gamma-ray spectrum obtained by plotting the readings of a multichannel analyser consists of two parts. There is a Gaussian distribution about that point corresponding to the gamma energy (the photopeak) and a continuum extending from zero energy to a point somewhat below the photopeak (Compton continuum). There may also be peaks from high energy photons due to pair production. Although all parts of the spectrum are characteristic of a particular energy, only the peaks are normally used to identify and measure a particular nuclide. The continuum, in fact, is regarded as an undesirable "background" in the measurement of photopeaks of lower energy.

The simplest measurements that may be made from a plotted spectrum are those of photopeak height or area using as a baseline the straight line between the valleys adjacent to the peak. Where there is no overlap between photopeaks this arbitrary method is useful and often surprisingly accurate.

In order to facilitate peak measurement several automatic methods of Compton removal have been

reported. Subtraction of the Compton obtained from a secondary detector¹⁾ and anticoincidence techniques measuring scattered photons^{2,3)} have been used but such methods have limitations in accuracy and sensitivity.

The more precise, though tedious, graphical method is that of repetitive subtraction of each component spectrum in turn (obtained from standards) starting with that of highest energy. Though this is the most frequently used method of analysis it makes use of only those measurements around the photopeak and after several subtractions have been made, the lower energy peaks become subject to relatively high statistical uncertainties. An automatic method of subtraction using a modified multichannel analyser has been described⁴⁾ which though avoiding the labour of graphical subtraction does not remove the subjective element.

Where the spectrum is obtained from a known mixture of nuclides one would expect the best method of minimising statistical errors to be the method of least squares. This has been used in the analysis of fall-out material by gamma spectroscopy⁵⁾ but the significance of the results was not

¹⁾ D. H. Peirson, *Nature* **173** (1954) 990.

²⁾ R. Hofstadter and J. A. McIntyre, *Phys. Rev.* **78** (1950) 619.

³⁾ J. K. Bair and F. G. Maienschein, *Rev. Sci. Instr.* **22** (5) (1951) 343.

⁴⁾ W. Lee, *Anal. Chem.* **31** (5) (1959) 800.

⁵⁾ P. F. Gustafson, *ANL-6104* (1960).

discussed. It is the purpose of this report to compare this least squares analysis with graphical methods.

It should be mentioned that a numerical method for the complete analysis of unknown gamma spectra has been described⁶). This requires a knowledge of the efficiency of a number of spectrometer channels for a similar number of energy ranges. Good results have so far been obtained where the number is small (10) but the method is not designed to overcome poor statistics.

2. The Principle of Least Squares Applied to Gamma Spectra

A gamma spectrometer including a multichannel analyser of " n " channels numbered $1 \dots i \dots n$, records the mixed spectra from a source containing " m " nuclides numbered $1 \dots j \dots m$. Standard sources of known activity of each nuclide are available. These and the unknown source are measured under identical conditions of source geometry and spectrometer parameters.

The count rate in channel " i " from standard " j " is a_{ij} and the count rate from the mixture b_i . If the ratio of the unknown activity to its corresponding standard is x_j , then we may write

$$b_i = \sum_{j=1}^m a_{ij}x_j + Z_i \quad (1)$$

where Z_i is a random error.

The best values of x_j are obtained by minimising R , the sum of the squares of Z_i

$$R = \sum_{i=1}^n Z_i^2 = \sum_{i=1}^n \left[b_i - \sum_{j=1}^m a_{ij}x_j \right]^2 \quad (2)$$

Ideally, the values of Z_i should have a common variance and equation (2) weighted accordingly. This added complication has not been introduced since it is unlikely to affect the accuracy of the results significantly.

R is minimised by differentiating equation (2) partially with respect to x_j and equating to zero.

Thus one obtains a series of " m " equations numbered $1 \dots k \dots m$ of the form

$$\sum_{j=1}^m x_j \sum_{i=1}^n a_{ik}a_{ij} = \sum_{i=1}^n a_{ik}b_i \quad (3)$$

In the simple case of three unknowns, the equations would be

$$x_1 \sum a_{i1}^2 + x_2 \sum a_{i1}a_{i2} + x_3 \sum a_{i1}a_{i3} = \sum a_{i1}b_i$$

$$x_1 \sum a_{i1}a_{i2} + x_2 \sum a_{i2}^2 + x_3 \sum a_{i2}a_{i3} = \sum a_{i2}b_i$$

$$x_1 \sum a_{i1}a_{i3} + x_2 \sum a_{i2}a_{i3} + x_3 \sum a_{i3}^2 = \sum a_{i3}b_i$$

where summations are over " n " channels.

If the equations (3) are written in the matrix form

$$Ax = y$$

then the solution is

$$x = A^{-1}y$$

The inverse matrix A^{-1} may be obtained by direct calculation where $m \leq 3$, but for higher values of " m " electronic computation is desirable.

The variance of x_j (the square of the standard deviations) is given by

$$VAR(x_j) = \frac{R}{n-m} [e_{jj}]^{-1}$$

where $[e_{jj}]^{-1}$ is the corresponding diagonal element of the inverse matrix A^{-1} .

Thus, from a spectrum of a mixture and the spectra of standards comprising the mixture one can obtain the best value of the ratios of each component in the mixture to its standard and also the standard deviations of those values. In this way all the points of the spectrum are utilised, statistical errors reduced to a minimum and no subjective errors introduced.

An Autocode programme has been devised for Ferranti "Mercury" computer and experimental verification of the least squares approach was made to evaluate its use in the quantitative interpretation of gamma spectra.

3. Apparatus

The scintillation spectrometer used a sodium iodide crystal ($3'' \times 3''$) canned in aluminium and optically coupled to a photomultiplier (E.M. Type 9531). The system was shielded by a lead "castle" of $4''$ thickness, the interior of which was thermostatically controlled. The output from the stabilised amplifier system was fed to a Hutchinson Scarrott pulse height analyser (A.E.R.E. Type 9531).

⁶) H. M. Childers, Rev. Sci. Instr. **30** (9) (1959) 810.

63). The contents of the analyser store were copied on to punched cards by an automatic read-out system⁷). The punched card data was presented in an octal (short binary) scale to accommodate the Hutchinson-Scarrott system. A further elaboration was the use of an automatic time controller designed to eliminate the need for paralysis correction⁸).

For convenience, the punched card data was usually copied automatically on to punched paper tape suitable for input to the "Mercury" computer.

Experimental

The objects of the experiments were

(a) to measure the accuracy of the least squares approach;

(b) to compare such results with alternative graphical procedures;

(c) to observe practical limitations in applications of the method;

(d) to compare the calculated standard deviation with the observed accuracy.

A series of six standard sources (table 1) were counted on the spectrometer for an effective period of ten minutes each. The sources were then counted in groups of 2, 3, 4 and 6 to provide simulated mixtures, three measurements being made in each case. The spectra of the "mixtures" were then analysed by least squares, the results being shown in table 2.

Since errors should depend upon the total activity measured, results are expressed as percentages of total activity and not as percentages of individual components of the mixture. In addition, table 2 shows the difference between the standard

TABLE 1
Sources used in experiments

Nuclide	Gamma energies (MeV)	Total γ counting rate (c.p.m.)
Cs ¹³⁷	0.66	2640.9
Sc ⁴⁶	0.89 1.12	8506.9
Mn ⁵⁴	0.84	1183.7
Zr/Nb ⁹⁵	0.72—0.76	4568.4
Co ⁶⁰	1.17 1.33	6100.4
Ru/Rh ¹⁰⁶	0.51 0.62	1330.4
Background		380.0

and measured quantity as an error, and also the calculated standard deviation (i.e. the 68% confidence level), given by eq. (4).

Graphical analysis by successive subtraction in one case of each mixture are shown in the same table for comparison. Fig. 1 shows the stripping procedure used in the most complex case and also the best fitting curve from the least squares analysis.

⁷ C. N. Davey and R. L. Elliot, *Nuclear Power* **3** (21) (1958) 19.

⁸ C. N. Davey, Private communication.

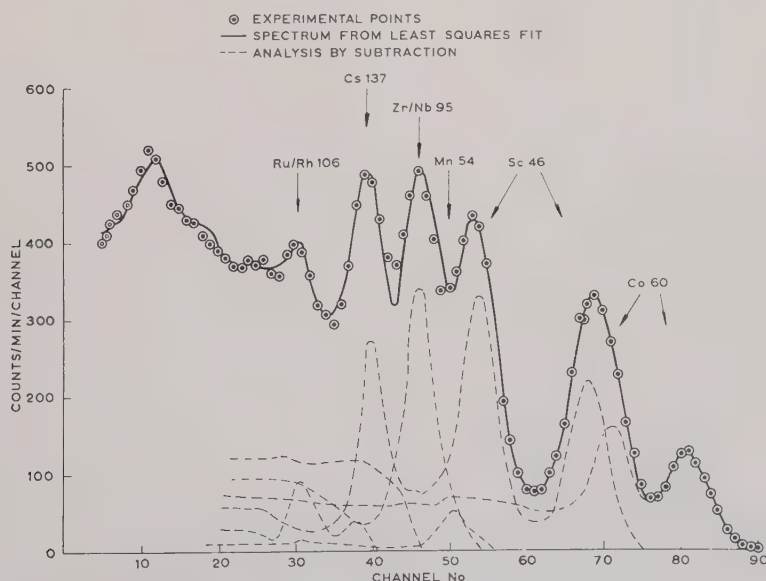


Fig. 1. Analysis of gamma-ray spectrum of six nuclides.

TABLE 2

Analysis of 2, 3, 4 and 6 component mixtures by least squares fit and by successive subtraction

Nuclide	% True counting rate	Calc. counting rate (c.p.m.)	Least squares fit			Successive subtraction		
			Calc. counting rate (%)	Std. dev. (%)	Error (%)	Calc. counting rate (c.p.m.)	Calc. counting rate (%)	Error (%)
Cs ¹³⁷	23.67	2697.4	24.21	0.26	0.54	2746.5	24.53	0.86
		2694.2	24.01	0.33	0.34			
		2705.6	24.23	0.26	0.56			
Sc ⁴⁶	76.31	8443.9	75.79	0.83	0.52	8447.3	75.47	0.84
		8526.5	75.99	0.48	0.32			
		8461.0	75.77	0.38	0.54			
Cs ¹³⁷	21.42	2665.4	21.20	0.26	0.22	2720.1	21.68	0.26
		2682.0	21.38	0.26	0.04			
		2705.1	21.67	0.31	0.25			
Sc ⁴⁶	68.98	8620.8	68.56	0.52	0.42	8464.4	67.47	1.51
		8639.7	68.85	0.52	0.13			
		8584.3	68.76	0.62	0.22			
Mn ⁵⁴	9.60	1288.6	10.24	0.40	0.64	1361.3	10.85	1.25
		1226.3	9.77	0.40	0.17			
		1194.5	9.57	0.45	0.03			
Cs ¹³⁷	15.63	2880.4	16.69	0.38	1.06	2651.4	16.19	0.58
		2793.8	16.30	0.40	0.67			
		2793.2	16.16	0.39	0.53			
Sc ⁴⁶	50.34	8923.7	51.71	0.75	1.37	8549.4	52.21	1.87
		8816.6	51.44	0.80	1.10			
		8976.4	51.95	0.77	1.61			
Mn ⁵⁴	7.00	809.6	4.69	0.40	2.31	898.4	5.49	1.51
		859.0	5.01	0.43	1.99			
		808.6	4.68	0.41	2.32			
Zr/Nb ⁹⁵	27.03	4643.7	26.91	0.47	0.12	4276.0	26.11	0.92
		4671.6	27.25	0.50	0.22			
		4701.7	27.21	0.48	0.18			
Cs ¹³⁷	10.86	2898.9	11.51	0.37	0.65	2891.7	11.46	0.60
		2974.7	11.82	0.41	0.96			
		2995.0	12.15	1.13	1.29			
Sc ⁴⁶	34.96	9173.8	36.43	0.85	1.47	8906.7	35.29	0.33
		9344.2	37.13	0.94	2.17			
		8700.0	35.28	2.38	0.32			
Mn ⁵⁴	4.87	850.7	3.38	0.38	1.49	710.2	2.81	2.06
		883.0	3.51	0.40	1.36			
		1485.1	6.02	1.82	1.15			
Zr/Nb ⁹⁵	18.77	4825.1	19.16	0.49	0.39	4568.4	19.82	0.05
		4779.9	18.99	0.56	0.22			
		4489.9	18.21	1.24	0.44			
Co ⁶⁰	25.07	6102.2	24.23	0.86	0.84	6100.4	24.66	0.41
		5891.0	23.41	0.84	0.66			
		5443.5	22.07	2.38	3.00			
Ru ¹⁰⁶	5.47	1330.8	5.28	0.50	0.19	1330.4	5.96	0.49
		1291.3	5.13	0.50	0.34			
		1547.0	6.27	1.63	0.80			

Background = 380 c.p.m.

Counting time = 10 min.

TABLE 3

Analysis of 3 component mixture with large statistical variations by least squares fit and by successive subtraction

Nuclide	Counting rate (c.p.m.)	% True counting rate	Calc. counting rate (c.p.m.)	Least squares fit			Successive subtraction		
				Calc. counting rate (%)	Std. dev. (%)	Error (%)	Calc. counting rate (c.p.m.)	Calc. counting rate (%)	Error (%)
Cs ¹³⁷	112.3	6.97	107.2	6.73	2.16	0.24	183.5	12.63	5.66
			121.4	7.50	2.44	0.53	172.4	11.11	4.13
			127.0	7.72	2.23	0.75	224.6	12.42	5.45
			131.5	8.10	2.10	1.13	222.5	12.59	5.62
Ru ¹⁰⁶	509.2	31.61	494.6	31.07	2.75	0.54	269.9	18.59	13.02
			507.3	31.36	3.07	0.25	371.7	23.93	8.68
			541.7	32.92	2.81	1.31	575.4	31.80	0.19
			491.9	30.30	2.66	1.31	458.2	25.90	5.71
Zr/Nb ⁹⁵	989.2	61.42	990.4	62.20	2.58	0.78	999.0	68.78	7.36
			989.0	61.14	2.88	0.28	1009.0	64.96	3.54
			976.5	59.36	2.64	1.06	1009.0	55.78	5.64
			1000.0	61.60	2.46	0.18	1088.1	61.51	0.09

background = 1831.6 c.p.m.
 time of count = 10 min.

Since these experiments were performed with reasonably high activity sources a further experiment was performed with large variations in the count from each channel. In addition to using sources of low activity, an artificially high counter background was introduced with a cobalt 60 source. The results of these measurements are given in table 3 and illustrated in fig. 2.

Finally as an example of the type of routine sample which is usefully analysed by this methods an air filter containing nuclear bomb debris was measured. The major fission product activities, present in such a sample is known to be Cs¹³⁷, Ru¹⁰⁶ (+ Ru¹⁰³) and Zr/Nb⁹⁵. Small photopeaks at 1.10, 0.84 and 0.44 MeV were assigned to the nuclides Zn⁶⁵, Mn⁵⁴ and Sb¹²⁵ respectively on the basis of previous examination of samples contaminated with fall-out activity⁹). The results of our analyses, here expressed in terms of measured gamma activity are shown in table 4.

Discussion of Results

The results of table 2 show smaller errors than one usually expects from routine gamma ray spectrometry. It will be noted that at the reason-

ably high counting rates used in these experiments the graphical method of successive subtraction shows an accuracy only slightly worse than the

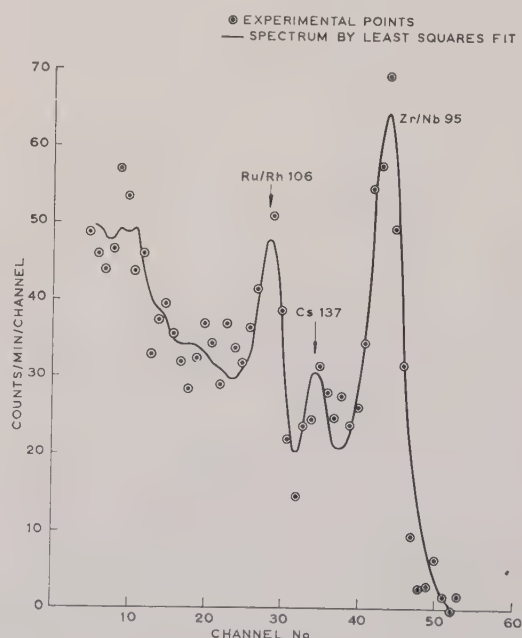


Fig. 2. Analysis of gamma-ray spectrum of three nuclides with large statistical variations.

⁹) J. Rundo and L. Salmon, Unpublished work.

results from least squares analysis. However, the graphical method is a subjective one and the accuracy is dependent upon the experience of the analyst. Where statistical variations in counting are large as in table 3 the errors from the graphical

TABLE 4
Analysis of air filter by least squares

Nuclide	Activity (γ m μ c)	Std. dev. (γ m μ c)	Mean (γ m μ c)
Cs ¹³⁷	1.45	0.05	1.49
	1.50	0.06	
	1.52	0.06	
	1.50	0.05	
Ru ¹⁰⁶	1.53	0.03	1.52
	1.54	0.04	
	1.50	0.04	
	1.52	0.03	
Zr/Nb ⁹⁵	4.43	0.06	4.40
	4.34	0.06	
	4.43	0.06	
	4.39	0.06	
Zn ⁶⁵	0.23	0.08	0.46
	0.21	0.08	
	0.23	0.08	
	0.26	0.07	
Mn ⁵⁴	0.53	0.06	0.23
	0.40	0.07	
	0.42	0.07	
	0.47	0.06	
Sb ¹²⁵	0.26	0.03	0.27
	0.32	0.03	
	0.30	0.03	
	0.29	0.03	

method are considerably worse than those obtained by calculation. Also the labour involved in performing the graphical subtractions is considerable. The results from least squares fit in table 3 are particularly gratifying when one observes the scatter of points in fig. 2.

It is not surprising to find that the errors in the results increase with the number of components in the mixture and that the worst results are obtained with a nuclide whose photopeak is "swamped" by an intense peak of similar energy (e.g. Mn⁵⁴ in the presence of Sc⁴⁶ and Zr/Nb⁹⁵, table 2).

Since the mathematical approach is objective it

would not be surprising to find occasional negative roots to the equations and hence the possibility of completely untrue results. Analyses carried out for six nuclides on samples actually containing only two or three, some negative results were obtained but these were close to zero. It is assumed that gross negative roots would only occur in a mixture of many more nuclides and conditions of large statistical variations in counting.

Least squares analysis applies to only one variable in $u = f(v)$, in this case the variable being the counting rate. No allowance is made for variations in u , the pulse height, that might occur during the period between the measurements of standard and sample. These fluctuations rarely exceed 1% gain and less in bias during a day. Accordingly artificial geometric and arithmetic changes were introduced (gain and back bias shift) of greater extent than should normally occur in order to observe the effect upon the analyses. It has been found that the greater errors are introduced but these are not gross. In fact it is probable that some compensation of errors between discrepancies in corresponding peaks and valleys takes place for small pulse height changes. Where the errors have been increased by gain and back bias shift there is a corresponding increase in the standard deviation.

The calculated values of standard deviations, to 68% confidence level, appear reasonable for two and three component mixtures (tables 2) where statistical variations in counting are small. In fact two-thirds of the errors lie within their corresponding standard deviations. For four and five components the calculated standard deviations are low whilst the consistently high values of standard deviation of table 3 are unexplained, but are probably due to the introduction of an artificial background.

6. Conclusions

The above results indicate that the analysis of scintillation spectra by least squares is more accurate, particularly when the statistical variations in counting are large, than by graphical means. The method provides values of standard deviation from the measurements and since computing techniques are used the results may be readily produced.

in any desired form. Thus the technique is particularly suitable to analysis of routine samples such as measurements of fall-out in air filters, rain, soil etc.

Acknowledgement

The author is particularly grateful to Mr. E. B. Fossey and Mr. B. Cooper of Theoretical Physics Division, A.E.R.E. for much helpful discussion.

ON TWO PULSE MODE AND IMPROVEMENT IN DEAD TIME OF DEKATRON DISPLAY ANALYSERS

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This paper describes a new "Two Pulse Mode" developed for making a GC10D (20 kc/s, single pulse drive) Dekatron adaptable for self "gating" and to be used as a 100 channel display element. This is the fastest Dekatron in the low price range and results in a considerable economy in capital cost. It is being used for the first time in a 100 channel analyser. The basic

design of this analyser is discussed and it is shown that its dead time of 140 μ sec compares well with those analysers using magnetic core storage and with identical performance. Certain additional new circuits have been developed for single pulse drive, used in individual channel storage. These are being reported else where in detail.

1. Introduction

When one estimates the upper limit of the speed of analysis of a kicksorter, required to be known for making accurate counting loss corrections, one has to take into account the contribution due to each of the three processes, namely, "pre-treatment", "channelization", and "registration"¹), to the overall "dead time".

The present day trend is towards making multi-channel analysers employing analog to digital conversion, because of their high stability, linearity, multiplicity and the lack of "relative drift"²). However, the process of analog to digital conversion is inherently time consuming and slows down the speed. Table 1, shows comparative dead times of conventional analysers using analog to digital conversion. For comparison the dead time of cascaded discriminator type analyser has also been given.

2. Dekatron Display Analysers

The Dekatron display analysers mentioned in table 1, possess the same advantages as those employing "core storage", except for longer dead time and larger size; and are superior in terms of simplicity, low capital cost etc. The author's own experience regarding Dekatron reliability has been very encouraging. Obviously, the Dekatron display analysers use the Kandiah³)-Chambers method of operating the display Dekatrons on "two pulse mode", wherein "gating" is performed directly on

the Dekatron. It has been a general practice to use GC10B (4 kc/s) Dekatron as display element.

The dead time of such an analyser is contributed by two major factors, one due to the process of analog to digital conversion, common to all such analysers mentioned in table 1. The other factor is mainly due to the time loss in the display. From table 1, the contribution to dead time due to the second factor for core storage type is about 35–50 μ sec while that for Dekatron display type is about 250–300 μ sec. This is primarily due to the use of slow double pulse Dekatrons (GC10B). Fast dekattrons like Sylvania 6909, 6910 (both 100 kc/s) are prohibitively costly for being used in a 100 channel display.

This paper deals with a new circuit developed for adapting GC10D (a single pulse drive Dekatron, max. speed 20 kc/s) to "two pulse mode", (with direct gating), for use as a 100 channel display element. It is worth noting that GC10D can operate upto 20 kc/s which brings down the dead time in the range of 40–50 μ sec (five times faster than GC10B, with a dead time of 250 μ sec). Consequently, with the new pulse drive, analysers with overall dead time of 135–145 μ sec could easily be designed using GC10D in the display. These the

¹) P. K. Patwardhan, J.S.I.R. **15A**, No. 10 (1956) 439.

²) A. B. Van Rennes, Nucleonics **10** (1952) 56.

³) K. Kandiah and D. W. Chambers, J. Brit. I.R.E., (1955) 227.

TABLE 1
Comparative dead time of various multichannel analysers

Type of analyser	Type of storage and display	Max. time for A-D. process (μ sec)	Time for the rest of the processing (μ sec)	Code oscillator frequency (Mc/s)	Channel selector	Max. no. of channels	Max. total dead time (μ sec)	Remarks (speed)
A Analog to digital conversion (similar to Canadian design)	Magnetic core storage C.R.T. display	100	35-40	1	M.B.S. tubes	100	140	Medium
B As above (similar to RCL, RIDL and Nuclear data design)	As above	128 256	20-25 20-25	2	M.B.S. tubes	256 512	150-155 275-280	Medium fast
C As above (similar to Philips)	Dekatron (GC10B)—display using Kandiah method of two pulse drive with electro-mech. register	250	50-400	0.4	RYG-10 tophotrons	100	600-700	Slow
D As above (improved)	As above	100	30-400	1	M.B.S. tubes	100	600	Slow
E Analog-digital conversion (our newly proposed)	Two GC10D followed by SODECO register, using new two pulse drive	100	35-40	1	M.B.S. tubes	100	140	Medium (as in 'A' above)
F Cascaded discriminators (any standard design)	Individual scaler storage per channel	Does not apply	About 20	—	Fast discriminators	50	20	Fast

possess the same dead time as core storage analysers, refer table 1. This is incidentally the lowest dead time for any Dekatron display analyser, since contribution to dead time due to analog to digital conversion process far exceeds that due to display and associated circuits. GC10D, is also a very low cost Dekatron (35 shillings).

3. The GC10D Dekatrons

This is the fastest Dekatron in the low price category and is ideal as a 100 channel display element but for the fact that it works on a single pulse drive and hence "gating" cannot be directly performed on it. This Dekatron consists basically of

the tube, with a high resistance in the anode circuit to limit the current to a suitable value, one of the anode cathode gap is ionized and a "negative glow" around the particular cathode is visible through the dome of the envelope.

4. New Two Pulse Mode

Figure 1 illustrates the new circuit, developed for running GC10D on a two pulse drive. Normally, the guides are held at a positive potential of 45–50 V obtained from neons as shown in the diagram. A negative rectangular pulse of > 150 V amplitude and $15 \mu\text{sec}$ width is applied to the first guide. This causes the glow to be transferred to the first guide

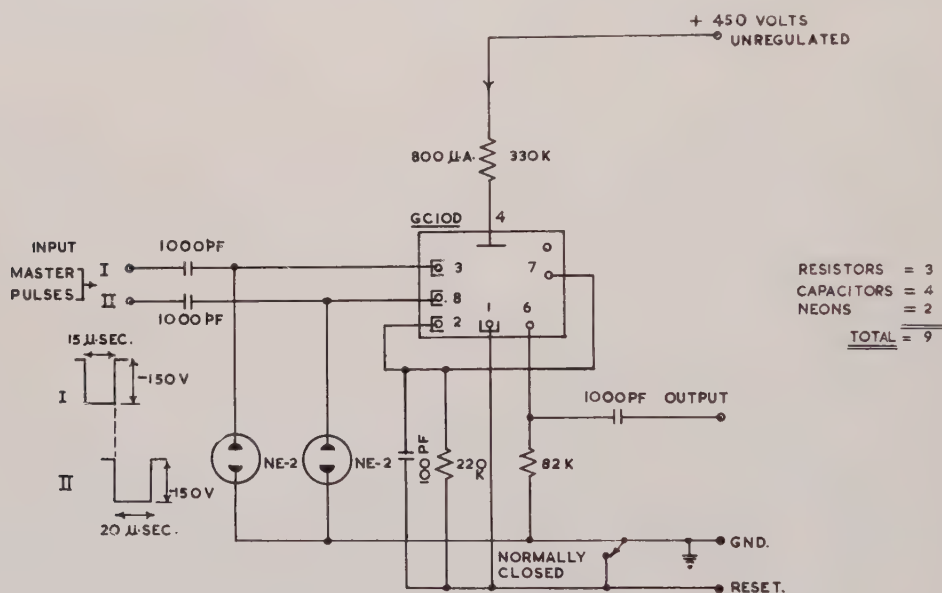


Fig. 1. New "two pulse" drive for GC10D with "gating".

40 cold cathode diodes in one envelope. The diode cathodes are rod shaped and arranged around a circular disc anode. Ten of the electrodes are known as cathodes, ten as first guides, the next ten as second guides and the last ten preceding the cathodes as third guides. Nine of the cathodes are internally connected, the tenth, brought out to a separate connection in the base of the tube, is the output cathode. All the ten first guides are connected together as are the ten second guides. The cathodes, first, second and third guides are intermeshed in cyclic order.

When a high potential (400–500 V) is applied to

adjacent to the cathode, where the glow initially centred. A second rectangular pulse of > 150 V amplitude and negative sign, with $20 \mu\text{sec}$ width is applied to the second guide, just after the completion of the first pulse. For convenience we shall call them Master pulses I and II. The glow rests on the second guide during the interval of the Master pulse II. The return of the first and second guides to the positive bias cause the glow to be moved to the third guide, from where, due to auto-transfer, the glow is finally transferred to the cathode, thus completing one count.

Circuit Tolerances

For biasing the guides 85A2, NE-2 and NE-51 neons have been tried and almost identical performance obtained. From the considerations of cost, low-priced NE51 and NE-2 neons are preferred. Both of them show better performance at higher frequencies compared to 85A2. The guide voltage is found to be non-critical. The range is quite wide from 40–85 V and the Dekatron has been successfully operated upto 20 kc/s. It will be further observed that the use of neons for providing bias is very satisfactory, replaces three components by one. Actually, only 20 neons are sufficient to provide bias to the first 100 Dekatrons in the entire 100 channel display. Ten neons for the 100 first guides and the other ten for the 100 second guides. Further, the use of neons obviates need for using stabilized voltages in the Dekatron drive circuit. In reality the whole of the 100 channel display needs no stabilized voltage line.

The value of coupling condensers is 1000 pF and it has been found that this too is not a critical value. Values from 0.01 μ F down to 500 pF have been tried with no change in performance. The value of Anode load is also not critical. This value is mainly determined by the intensity of the glow desired under normal room illumination. 330 k Ω , which passes 800 micro-amps through the tube, is quite adequate.

Regarding Master pulses the observation has been that the width of the first Master pulse could easily be reduced to 10 μ sec without affecting performance. Similarly, the second master pulse could be reduced down to 18 μ sec with identical performance, however, below 18 μ sec the performance is affected. Thus the total time loss between two counts is of the order of 35–40 μ sec including auto-transfer time. The Dekatron has been successfully operated upto 20 kc/s with excellent performance.

6. Proposed 100 Channel Analyser System

Figure 2 indicates the block diagram of the 100 channel GC10D dekatron display.

As seen from the diagram the guide I s' of all the rows (ten Dekatrons per row and ten such rows) and guide II s' of all the columns (similar to rows) are supplied with Master pulses I and II, respectively,

and the Dekatron on the crossing of the selected row and column is the only one to receive both the Master pulses and hence will register a count. This is how "gating" is performed. The selection of the particular row and column is brought about by the MBS (Magnetron Beam Switching tubes) channel selector.

Twenty 6 AS6 gate tubes, ten for "units" and ten for "tens" are used. The suppressor grids of these valves are operated between 0 and + 25 V. This d.c. bias for the suppressor grid is obtained from the channel selecting MBS tubes, which count the "code pulses" from the analog to digital convertor. The rest of the operation of the analyser as seen from fig. 2, is self explanatory.

Considering 100 μ sec as maximum dead time for analog to digital process and 40–50 μ sec in display and associated circuitry, the estimated overall dead time of the analyser is about 140–150 μ sec. Each channel uses either, four GC10D Dekatrons or, two GC10D Dekatrons followed by a Sodeco four digit register, for storage of channel counts. It is found out from statistical considerations and from the estimation of counting losses per channel, that an individual channel counting capacity of 2000 counts/second is quite adequate for handling random spectral pulses upto the maximum capacity of the analyser. This has also the advantage of large storage capacity 999999 counts. Development of a new circuit for the single pulse operation of GC10D has resulted in a considerable saving of components, 9 for the new circuit as against 16 for the conventional drive.

One can see the immense cost saving that would result for a 100 channel display. More over the whole of the display does not need stabilized voltage line and results in consequential simplification of circuitry. The complete details of the plug-in-units and the associated circuitry are being reported else where.

Acknowledgement

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CIRCUIT DE COINCIDENCE A DIODES TUNNEL

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A fast coincidence circuit with amplitude discriminator using tunnel diodes is described. The resolving time of 5 nanoseconds is obtained. The threshold of the circuit is adjustable from some

tens millivolts to one volt. The operating range may be extended to 10 volts.

La plupart des circuits de coïncidence rapides utilisés sont des circuits d'addition. Des impulsions d'amplitude et de durée constantes sont envoyées dans un étage mélangeur. Un discriminateur placé en aval du mélangeur permet d'extraire les signaux de coïncidence.

ment totalement différent. La durée de ses impulsions dépend principalement des éléments passifs L et r ainsi que de l'énergie de l'impulsion d'attaque et ne dépend pratiquement pas de la capacité parasite C . Le circuit est polarisé exactement comme le multivibrateur déclenché en un point stable A (I_R, V_R) fig. 3. Une impulsion de courant d'amplitude $I_C = I_P - I_R$ déplace quasi instantanément le point de fonctionnement en B. Le basculement de la diode tunnel établit un courant dans

Description des circuits de mise en forme

Nous avons décrit, dans un premier article à paraître dans Nuclear Instruments; un circuit de

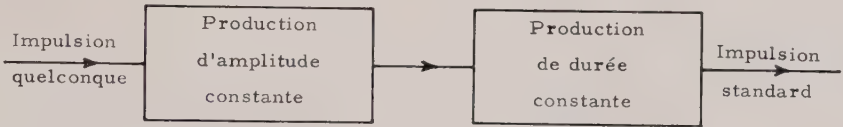


Fig. 1. Principe de la mise en forme des signaux.

mise en forme dont le principe est donné par le diagramme fonctionnel de la figure 1.

Les triggers émettent des impulsions à amplitude constante. Ils sont constitués d'un quadripôle en L comprenant dans la branche série une résistance R et dans la branche parallèle la diode tunnel. Ce circuit simple et stable est déclenché par des signaux d'amplitude de quelques volts. Il s'est avéré nécessaire de mettre au point un circuit analogue plus sensible qui répond à des signaux de quelques dizaines de millivolts d'amplitude.

Un circuit multivibrateur monostable à diodes tunnel classique (fig. 2) a permis d'atteindre des performances intéressantes en sensibilité. Nous marquons l'identité de la dispositions des éléments avec celle du multivibrateur déclenché, décrit dans notre premier article. Cependant les valeurs des éléments lui confèrent un fonctionne-

l'inductance L . L'augmentation du courant dans celle-ci diminue le courant diode et le point de fonctionnement se déplace de B vers C. Une fois le

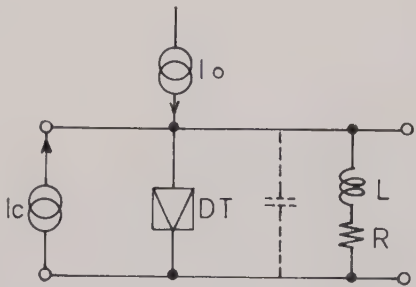


Fig. 2. Multivibrateur monostable.

point C atteint, le circuit revient à son état initial en passant par le point D.

En plaçant le point A près du point P nous pouvons rendre le circuit très sensible. Le seuil de

déclenchement est donc conditionné par l'emplacement du point A sur la caractéristique statique de la diode tunnel.

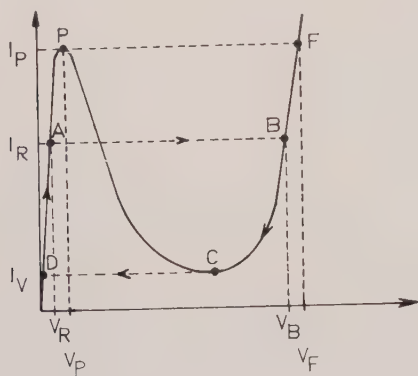


Fig. 3. Fonctionnement du monostable.

Le seuil, c'est à dire l'impulsion de commande minimum nécessaire pour déclencher le monostable est déterminé par le courant

$$I_{C \min} = I_P - I_R.$$

Si le point de polarisation varie d'une quantité ΔI_R et en admettant que le point P reste stable on obtiendra une variation du seuil de

$$|\Delta I_{C \min}| = |\Delta I|$$

$$\frac{\Delta I_{C \min}}{I_{C \min}} = \frac{\Delta I_R}{I_{C \min}} = \frac{\Delta I_R}{I_R} \times \frac{I_R}{I_{C \min}}.$$

La variation relative du seuil est donc égale à celle de la polarisation multipliée par le rapport

$$I_R / I_{C \min}.$$

Par exemple: pour

$$I_R = 10 I_{C \min}$$

ou encore

$$I_R = \frac{10}{11} I_P$$

la stabilité du seuil est 10 fois plus faible que la stabilité du courant de polarisation.

Pour la production d'une impulsion de durée constante, nous utilisons à nouveau un multivibrateur déclenché.

2. Description du circuit de coïncidences

Le circuit de coïncidences est constitué par un montage monostable classique décrit ci-dessus comprenant deux ou plusieurs résistances série d'entrée suivant le nombre de voies de coïncidences. On attaque ce circuit mélangeur par les impulsions standards issues des multivibrateurs déclenchés. La polarisation du circuit est telle, qu'une impulsion seule n'arrive pas à déclencher le circuit; par contre deux impulsions simultanées s'additionnent et font basculer le montage. Une impulsion standard est alors émise.

Les impulsions standards ayant un temps montée et de descente non négligeable, la polarisation de la diode tunnel conditionne le temps de résolution. La figure 4 indique les différentes

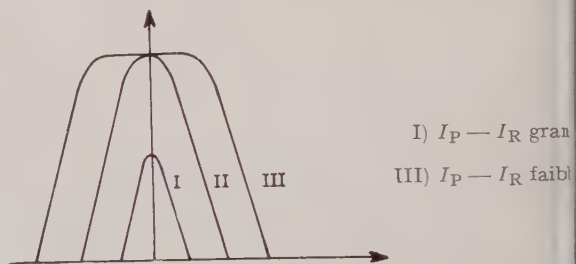


Fig. 4. Courbes de résolution en fonction de la polarisation.

courbes de résolution que l'on obtient suivant la polarisation de la diode tunnel en tenant compte des fluctuations de temps introduites par les détecteurs.

3. Résultats expérimentaux

Le montage a été étudié à l'aide de photomultiplicateurs RCA 6342 A et d'une source de ^{22}Na utilisant différents scintillateurs.

L'ensemble du circuit de coïncidence est donné par le schéma fig. 5. Celui-ci est sensible à quelques dizaines de millivolts, le seuil peut être réglé jusqu'à 1.3 volts, et les impulsions d'entrée peuvent atteindre 10 V.

La figure 6 représente les trois courbes de résolution suivantes:

a. Les signaux de coïncidence artificielle obtenus

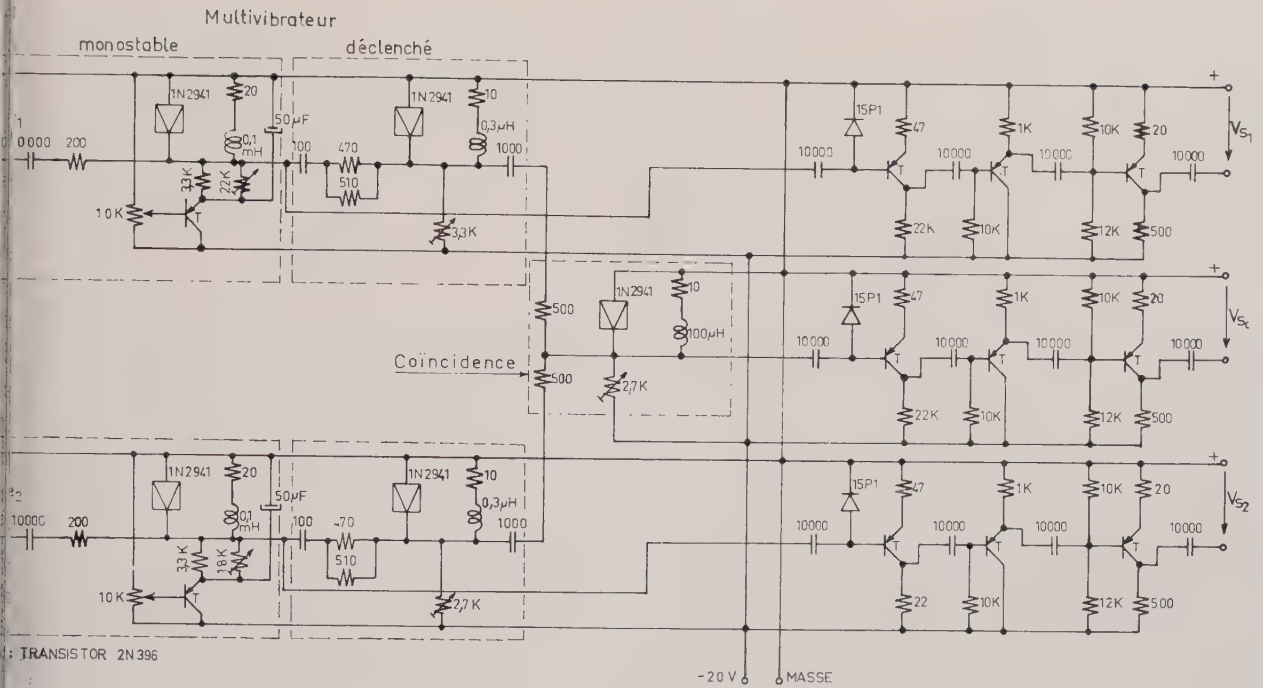


Fig. 5. Circuit de coïncidence à diode tunnel.

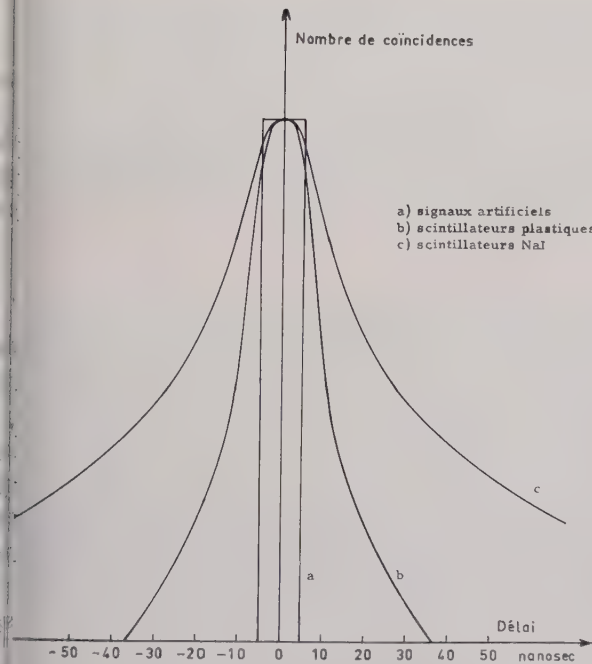


Fig. 6. Courbes de résolution.

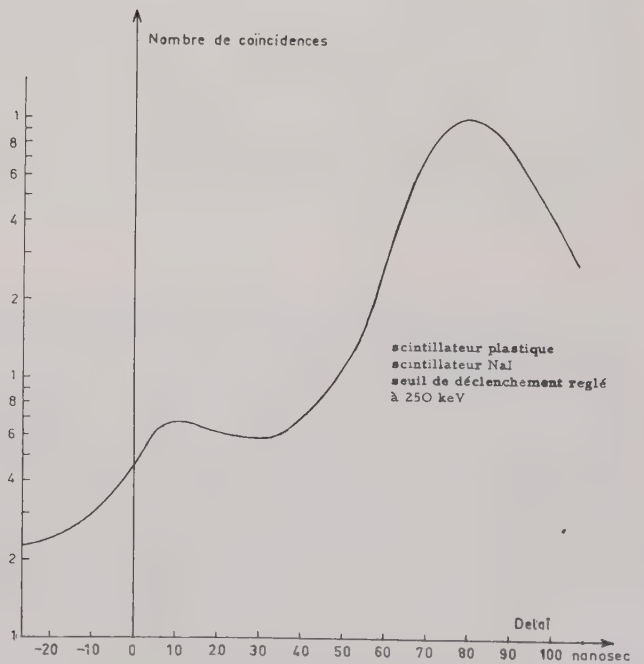


Fig. 7. Courbes de résolution.

à l'aide d'un générateur à relais de mercure Tektronix 108.

b. Les signaux de coïncidence obtenus à l'aide de scintillateurs plastiques.

c. Les signaux de coïncidence obtenus à l'aide de scintillateurs NaI.

Les seuils des circuits d'entrée sont placés légèrement au-dessus du bruit.

Dans le tracé de la courbe de résolution de la figure 7, on remarque une bosse située à 70 nanosecondes du sommet de la courbe. Des mesures effectuées à un analyseur d'amplitude multicanaux ont montré que ces coïncidences sont dues au mélange des impulsions provenant des rayonnements gamma de 1.28 MeV détectés par le cristal NaI, avec les impulsions des rayonnements gamma de 511 keV détectés par le scintillateur plastique.

Pour conserver un bon temps de résolution avec seuil sur une voie rapide, il est nécessaire d'attaquer le circuit par des impulsions à montée rapide (figure 8).

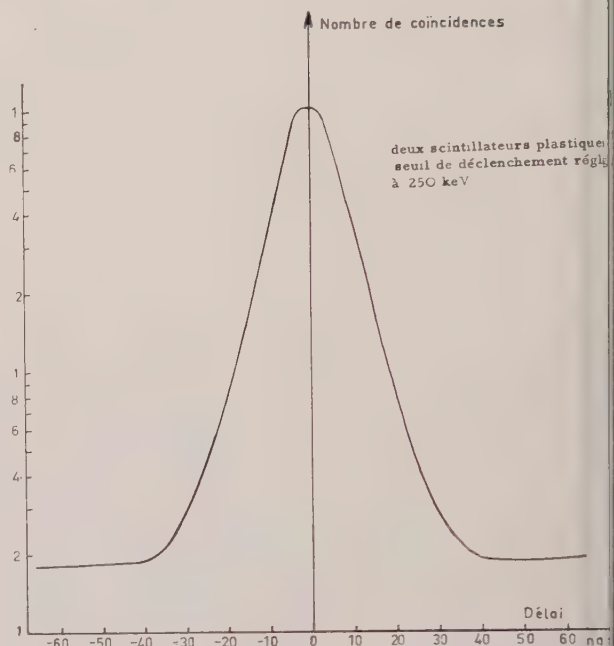


Fig. 8. Courbes de résolution.

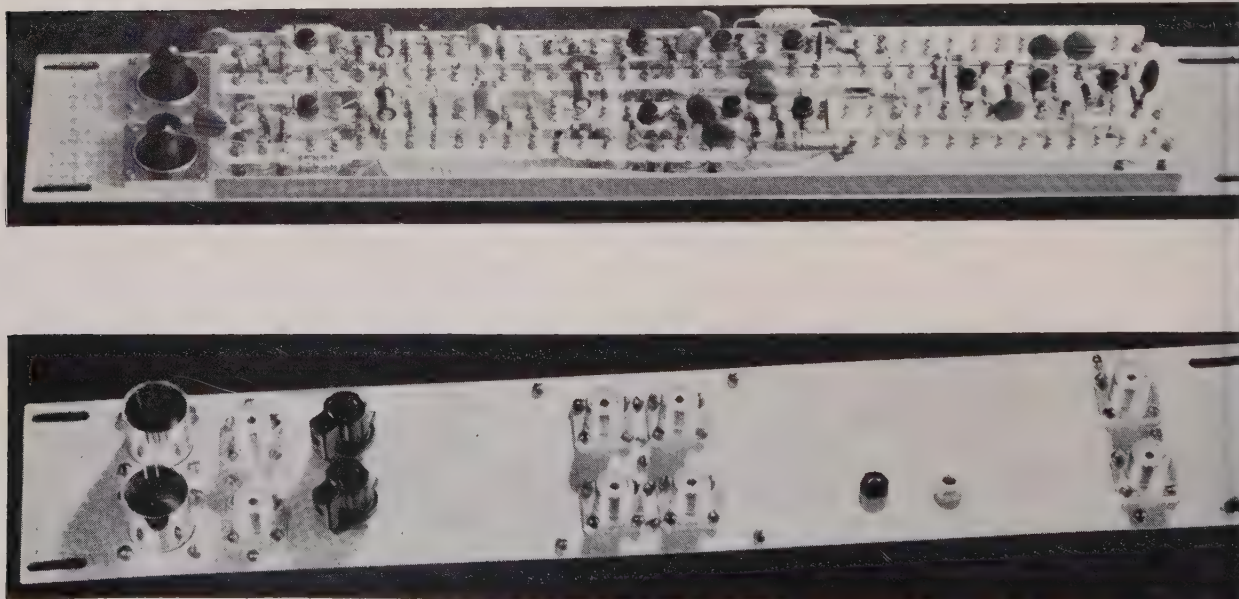


Fig. 9. Photographies du circuit à coïncidence utilisé pour les mesures.

EXPERIENCES ON THE APPLICATION OF THE SUM-COINCIDENCE METHOD

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In the study of cascade γ -processes, Hoogenboom's sum-coincidence method¹⁾ has proved exceedingly useful. This method has made it possible to detect transitions of very low intensity, and possesses advantages for measurements of angular correlation as well. As the author's experience shows, in

the sum-coincidence spectrum, false peaks or background levels of a certain height may appear in part of the discrimination region. This is partly due to instrumental reasons, partly to the characteristics of the method itself, and it depends on the properties of the decay scheme under study.

Introduction

In 1958 A. M. Hoogenboom reported on a new method by means of which he succeeded in increasing the energy-resolving power of scintillation gamma spectrometers and in realizing the aim that "full energy" peaks should appear in the spectra. In addition, his method has its advantages also for measurements of angular correlation.

This paper deals with some properties of the method that have been revealed to us. Furthermore, a graphic method is suggested which facilitates the review and interpretation of all the properties of the method. By its means the confusing background appearing in the sum-coincidence spectra can be easily identified and corrected.

Subject to given conditions it is practicable to perform the analysis of unknown gamma spectra in the following manner: First the single scintillation gamma spectrum should be taken by means of a well collimated beam. Besides the background and gamma rays scattered from the environment, this spectrum contains only peaks corresponding to the individual gamma transitions. It means that sum-peaks arising from the coincidence of two or more transitions are not present. If, subsequently, the spectrum is taken with a well-type crystal, by summing method^{2,3)} the gamma-rays in cascade

may be simultaneously absorbed and give rise to sum peaks in the sum spectrum. From the comparison of the sum spectrum and the spectrum taken by a collimated beam, various conclusions may be drawn regarding the decay scheme.

On applying the sum-coincidence method, it is practicable for the analysis to set the sum channel successively at the full energy peaks of the sum spectrum so that we proceed from the higher energies to the lower ones. From the sum spectrum it can be determined which one of the maximum energies in the decay scheme arises directly or by virtue of a cascade transition. On applying Hoogenboom's method, as a first step, it is practicable to set the sum channel at this peak energy. In this case, the sum coincidence spectrum will arise in the manner known from literature¹⁾.

If for the purpose of a further study on cascade transitions the sum channel is orderly set at photopeaks of lower energy, not only the photopeaks of gamma rays in cascade with one another, the sum of whose energies correspond to the new setting will appear, but also some other confusing background impulses. The reason for this is that in addition to the sum of the photopeaks with lower energy in question, the sum of certain components of the spectrum of gamma rays with higher energy that have been measured and are in actual coincidence, will also equal the value of the sum channel. The background, too, may be of a great importance. Its spectral distribution greatly depends on the position of the sum channel.

¹⁾ A. M. Hoogenboom, Nucl. Instr. **3** (1958) 57.

²⁾ D. C. Lu and M. L. Wiedenbeck, Phys. Rev. **94** (1954) 501.

³⁾ R. K. Girgis and R. Van Lieshout, Nucl. Phys. **12** (1959) 2.

By means of the graphic method to be described further on, it can be determined exactly what spectral distribution, with what intensity is revealed by the appearing background.

2. Background of Instrumental Origin

In the coincidence spectrum, false peaks may be produced by back scattering of gamma rays from one crystal to the other, as shown also by Hoogenboom. The discrete energy character of the background arising in this manner can be accounted for by the fact that back scattering gamma rays possess a discrete energy. Namely, the gamma rays scattered in an angle defined by the Compton effect, as is well-known, fall in a narrow energy-band.

The site and number of peaks deriving from backscattering can be elucidated in advance by the following process of reasoning:

Besides the sum peak, only peaks corresponding to such impulses in coincidence with one another may appear in the sum-coincidence spectrum whose energy-sum exactly equals that at which the sum channel is set.

The knowledge of the energy of gamma rays to be measured includes also that of the energy of back-scattered gamma rays. These will be the peaks of lowest energy in the sum-coincidence spectrum. In accordance with the above, there will appear a peak at each energy of the kind that is in coincidence with the corresponding peak of back scattering and the energy of which brings the energy of the peak of back scattering up to the energy value defined by the sum channel (see legend to fig. 1).

In case of two gamma lines, eight peaks may arise from back scattering. Quite often, the two peaks of back scattering coincide and the eight peaks are therefore reduced to six.

The peaks arising from back scattering can be reduced to a great degree by means of an anti-Compton shield placed between the two crystals. By using this shield, it can also be decided which ones of the peaks appearing in the spectrum derive from back scattering.

Confusing background in the sum-coincidence spectrum may be further due to the overloading of the apparatus in case of a high source intensity. On such an occasion, two impulses are superposed within the resolving time and yield an impulse

magnitude, that can equal the energy value of the sum channel. In this case, an entirely false sum coincidence spectrum is obtained. A typical example is given in fig. 2. On taking the gamma spectrum of Fe^{59} , the sum channel was integrally set at 1.7 MeV, that is, every signal corresponding

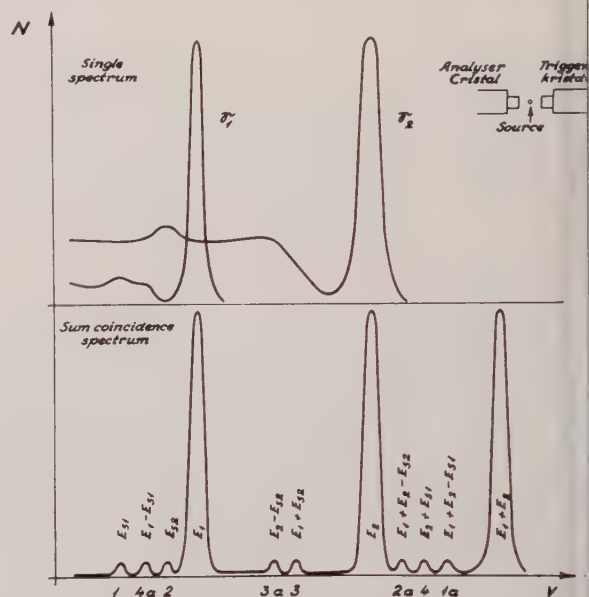


Fig. 1. False peaks arising from back-scattering in the sum coincidence spectrum. The energy values pertaining to back-scattering peaks of gamma-rays in coincidence (γ_1 and γ_2) of energies E_1 and E_2 respectively are designated by E_{S1} and E_{S2} . Peaks 1 and 2 arise when the respective energies of E_{S1} and E_{S2} are absorbed in the analyser crystal and at the same time ($E_1 + E_2 - E_{S1}$) and ($E_1 + E_2 - E_{S2}$) in the trigger-crystal, that is the back-scattered portion of γ_1 and γ_2 respectively get into the analyser crystal. The complements of these are peaks 1a and 2a respectively at the rise of which energy ($E_1 + E_2 - E_{S1}$) or ($E_1 + E_2 - E_{S2}$) is respectively absorbed in analyser-crystal, whereas only E_{S1} or E_{S2} respectively gets into the trigger-crystal. Peaks 3 and 4 respectively arise so that respective energies of ($E_1 + E_{S2}$) and ($E_2 + E_{S1}$) get into analyser-crystal, and at the same time the respective energy ($E_2 - E_{S2}$) and ($E_1 - E_{S1}$) get into the trigger-crystal. The complements of peaks 3 and 4 are denoted 3a and 4a.

to energies higher than 1.7 MeV was allowed to enter the discriminator in the sum channel. In the case under consideration, these signals could only be due to overloading, as the maximum sum energy of γ -rays arising from the decay of Fe^{59} , is 1.1 MeV. It is characteristic of the obtained coincidence spectrum that the spectrum is quite asymmetric.

Overloading can be avoided by applying a coincidence circuit of good resolving power or by using a source of lower intensity. In the case of applying a slow-fast coincidence circuit, however, the sum peak will not appear in the sum-coincidence spectrum.

impulses in the sum-coincidence spectrum which are in coincidence and the sum of their amplitude falls in the interval defined by the sum channel. Thus on the basis of the single spectra, the amplitude distribution of the sum-coincidence spectrum can be constructed. In order to meet this task, first

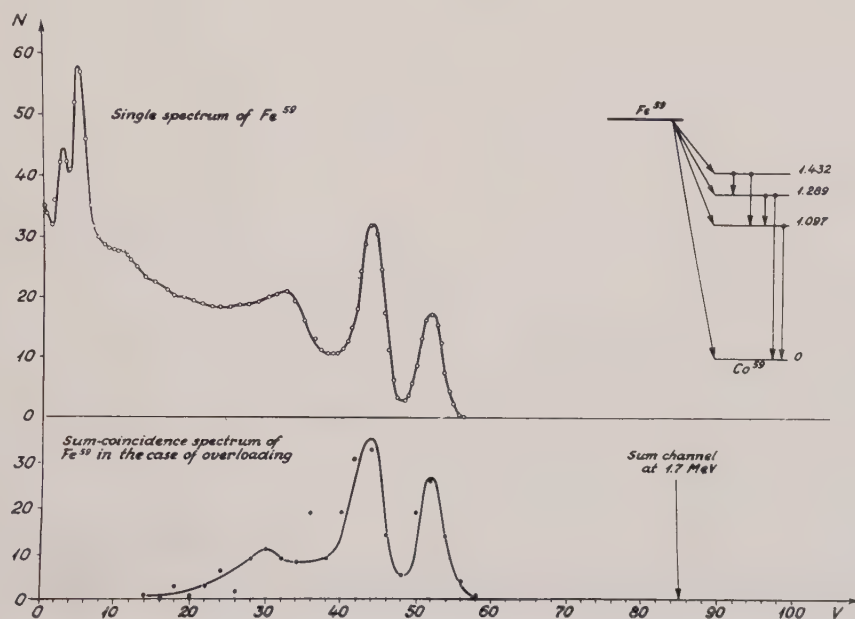


Fig. 2. The sum-coincidence spectrum of Fe^{59} . The sum channel has been integrally set at 1.7 MeV. The obtained coincidence spectrum is due to an instrumental overloading.

Graphic Method for Constructing a Coincidence Spectrum to be Expected

In the course of measurements, the problem may repeatedly arise whether the obtained coincidence spectrum has not got distorted by some effects, which were described in the foregoing part of this report. The confusing background due to these effects can be satisfactorily eliminated by properly choosing the experimental conditions. In contrast, when the sum channel has to be set at lower energy values than the maximum-sum peak, for the purpose of studying cascades of lower energy, such disturbing conditions may develop that cannot be eliminated owing to the character of the method and the properties of the decay scheme under study.

A graphic method was developed to study sum-coincidence spectra and to analyze the disturbing effects. It was based on the appearance of all the

of all, the spectral distribution of the two gamma radiations in coincidence has to be known, as it can be seen in the uppermost line of fig. 3. The shape of the gamma spectrum of a given monoenergetic gamma radiation depends on the energy of the radiation in question, of the size of the crystal as, well as the measuring geometry.

In this case, it is appropriate to take the standard spectra by means of the given apparatus, when sources yielding monoenergetic gamma rays of different energies are used. Plotting the characteristic data of the spectra, (such as the half-width of photopeak, the height of the Compton-region relative to the photopeak, the site of the maximum energy of the Compton region, etc.) in the function of energy, such series of curves are obtainable by means of which we can draw the shape of the spectrum (of an arbitrary energy and monoenergetic gamma radiation) arising in the

scintillation crystal. The peaks deriving from back scattering which appear in the scintillation spectrum and arise at about 200 keV in a radiation of about 1 MeV are not to be taken into consideration

as they exert an effect only if the shielding between the two crystals is unsatisfactory. (See the foregoing paragraph.)

At a further stage of constructing the sum-

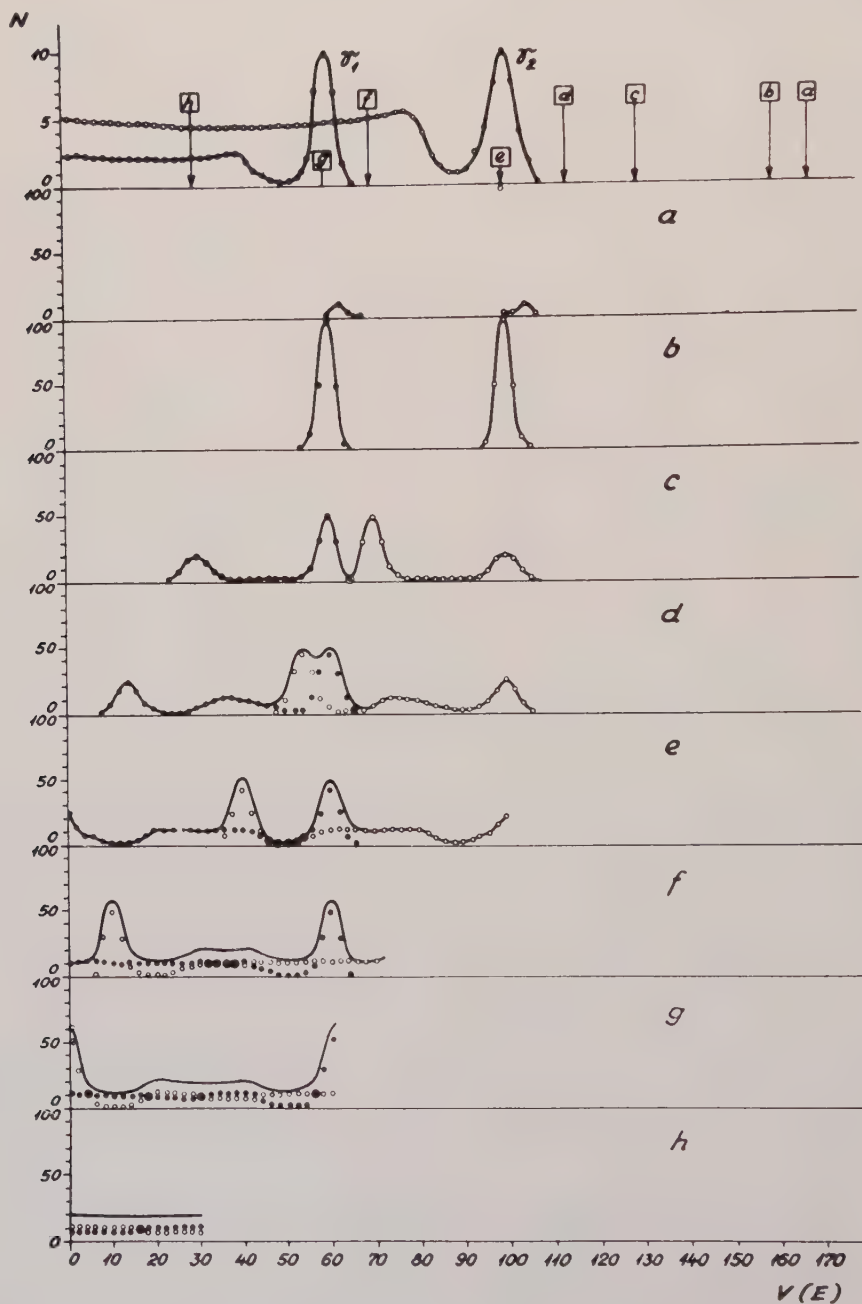


Fig. 3. The constructed shapes of the sum-coincidence spectrum while the sum-channel was successively set at energies *a*, *b*, *c*, *d*, *e*, *f*, *g* and *h*. The black dots denote the component spectrum of the sum-coincidence spectrum which arises by γ_1 getting into the analyser crystal and by γ_2 giving the trigger signal in the

other channel. The empty dots designate the complementary component spectrum, in the case of which, on the other hand, is γ_2 that gets into the analyser crystal. The actually measured resultant sum-coincidence spectrum is designated by a continuous line.

coincidence spectrum, the point must be marked upon the energy scale at which the sum channel is to be set (e.g. b in fig. 3). Subsequently, the height pertaining to every energy (number of impulses) of the scintillation-spectrum associated with γ_1 should be multiplied by the height pertaining to the energy of γ_2 at which the previously chosen point denoting the site of the sum channel in the diagram is obtained from the sum of the two energies. The resulting products are successively plotted below the corresponding energy values of γ_1 (black dots in the coincidence spectrum of fig. 3). The process represents the fact that while the analyser crystal renders signals of different amplitudes with different probability when detecting γ_1 , the trigger crystal detects γ_2 in a similar way. The product of these probabilities is proportional to the probability of the sum channel rendering a signal. In order to obtain the entire coincidence spectrum, this process is to be repeated also in the case of γ_2 (empty dots in the coincidence-spectrum). The latter case represents the detection of γ_2 in the analyser crystal, while γ_1 is absorbed in the trigger crystal. The obtained sum of the spectra represents the distribution of the sum-coincidence spectrum.

Case b of fig. 3 shows the case when the sum channel is set exactly at the sum of γ_1 and γ_2 . Case a illustrates how the coincidence spectrum gets distorted if the sum channel is not set exactly at the sum peaks. Different settings are represented by c, d, e, f, g and h . In this way, it is possible—by means of this graphic method—to construct the background (false peaks)—in the sum-coincidence spectrum—which arises when the coincidence of gamma rays with lower energy are investigated in the presence of a line or lines of higher energy, likewise in coincidence, by means of the sum-coincidence method. In such a case, the background originating from γ_1 and γ_2 is of the shape given by the graphic method and its intensity, as compared with case b , can be stated, provided the channel width has not been changed in the sum channel. For this reason in the course of construction, it is appropriate to choose identical heights for γ_1 and γ_2 . In case b , the value of the counting rate corresponding to the peaks appearing in the sum-coin-

cidence spectrum is obtained by measurement. With this in our possession, the absolute value of the background can be determined by the graphic construction, and it can be corrected.

4. Some Properties of the Sum-Coincidence Method

The graphic process illustrates also some fundamental properties of the sum-coincidence method, e.g. the improvement of half-width, the peaks in the spectrum being, pair by pair, of identical half-width and height, the resolving power deteriorating in case of bad setting (that is, not precisely at the sum peak), the decrease of intensity and shifting of peaks in the sum-coincidence spectrum.

Other properties of the method can also be read. If we descend with the sum channel from the value of the sum peak associated with $(\gamma_1 + \gamma_2)$, then the peak pertaining to the photopeak of lower energy (γ_1) will give the maximum intensity in the coincidence spectrum, and it will not change the position of the peak, at whatever value above $E\gamma_1$ the sum channel may be set. This is responsible, e.g., also for the phenomenon that by applying to a great channel width in the sum channel the peak pairs in the sum-coincidence spectrum will not have identical half-width and height, but invariably those of lower energy will be the narrower and higher ones.

At the construction shown in fig. 3 the width of the sum channel was supposed to be infinitely narrow. This supposition is not seriously disturbing until the width of the sum channel reaches that of the narrowest photopeaks in the spectrum. The effect of a great channel width can be well illustrated by the graphic method if, at the site of setting the sum channel, not one but more spectra are constructed within the limits of the channel and summarized.

If the analyser and trigger crystal do not possess identical properties (e.g. they are of different size), it means that with γ_1 and γ_2 , spectral shapes of γ'_2 and γ'_1 will be respectively associated, where γ'_1 and γ'_2 are spectra produced by the trigger crystal. (The case is similar when the amplification factors of the two channels are not exactly identical.) Thus the use of different size crystals will result in the

asymmetry of the coincidence spectra even in the case of a small channel width. That is to say, if the analyser is small and has good spectroscopic properties, while the trigger crystal is large and comparatively bad, then the peaks of lower energy will be higher and narrower than those of high energy. If the roles of the crystals are interchanged, so are the relations in the spectrum. This asymmetry is noticeable if the energy difference between γ_1 and γ_2 in cascade is great.

It is to be noted that when γ_1 and γ_2 appear in the single spectrum with quite different intensities it will naturally not effect the shape of the sum-coincidence spectrum. Namely, in such a case the excess impulses of the line with a higher intensity originate from some other transition or transitions (β , γ etc.), and these excess impulses will not coincide with the line of lower intensity. Thus,

under symmetric experimental conditions, the peaks pertaining to γ_1 and γ_2 in the sum-coincidence spectrum will be always of identical intensities.

In conclusion, attention should be called to the fact that the sum-coincidence method is—first of all—suitable for the investigation of two-stage cascades. The appearance of peaks being in a three-stage cascade has a probability (intensity) one or two less in order of magnitude than that of the peaks pertaining to the two-stage cascades, in the sum-coincidence spectrum. This is evident from considerations regarding the solid angle and efficiency of detection in coincidence measurements.

Thanks are due to professor A. Szalay, director of this Institute for his valuable support and genuine interest.

ISOTOPE PRODUCTION WITH THE NUFFIELD 60-INCH CYCLOTRON

Part 1

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The bombardment conditions and target techniques currently used for isotope production with the Nuffield Cyclotron are

briefly described. Some estimates of isotope production yields are given.

1. Introduction

Since the Nuffield Cyclotron became operative rather more than ten years ago it has been used for about 30% of its working time for the production of radioisotopes. Some of these are used by research workers in the Physics Department of the University of Birmingham, where the machine is located, but the majority have been supplied to other users in many parts of the world either directly or through the agency of the Radiochemical Centre at Chesham. The ever-increasing interest in, and demand for, cyclotron-produced isotopes encourages us to believe that isotope users, actual and potential, will be interested in an account of bombardment and handling techniques which have been developed.

2. Bombardment Conditions and Targets

Targets may be bombarded between the cyclotron dees in the vacuum tank, or outside the machine in a special exit port. In the former case the target material must be able to withstand very high temperatures in vacuo because of the energy dissipated by the incident ions. These may be protons, molecular hydrogen, deuterons, helium-3 or helium-4 ions with energies which may be controlled up to a limit of about 9.8 MeV per mass unit. The actual energy obtained depends on the radial position of the target in the cyclotron and in practice this can be in the range 5 to 9.8 MeV per mass unit of bombarding ion. The energy spread is of the order of 0.1 MeV per nucleon. The current of

ions is of the order tens or hundreds of microamperes, the upper limit being imposed in general by the thermal characteristics of the target rather than by the capabilities of the cyclotron. Near the maximum radius of the machine some 90% of the accelerated ions would fall in a target area about 5 mm × 20 mm measured at right angles to their direction of motion. The former figure roughly represents the separation between successive orbits in the stream of ions and the latter is a measure of the focussing at right angles to the plane of the orbits. Clearly some advantage is to be gained by presenting the target face at a glancing angle to the stream. By this means an area of several square centimetres may be irradiated, although far from uniformly. Larger areas may also be used if a lower bombarding energy can be utilised, because the separation between successive orbits is greater at smaller radii and the vertical focussing is worse. Nevertheless there are few target materials which will withstand a total power dissipation of more than three kilowatts, which would occur, for instance, with a current of 200 microamperes of deuterons at 15 MeV. (See table 1.)

Considerations of power dissipation limit the materials which can be successfully bombarded to those – generally pure metals or alloys – which can be effectively bonded to water-cooled copper blocks or themselves be formed into blocks having suitable water-cooling channels. We now use four standard sizes of blocks, which are illustrated in Fig. 1 (a), (b), (c), (d). Of these 1(a), 1(b), 1(c) are

TABLE I
Isotope production data

Isotope production reaction	Particle energy (MeV)	Total power (kW)	Target type	Yield (mc/h)	Means of attaching target material to target head
$\text{Mg}^{24}(\text{d}, \alpha)\text{Na}^{22}$	15	4.5	d	0.45 (a)	—
$\text{Ti}^{48}(\text{d}, 2\text{n})\text{V}^{48}$	19	5	d	20 (a)	—
$\text{Fe}^{56}(\text{d}, \alpha)\text{Mn}^{54}$	19	2	b	0.03 (a)	"Easiflo" hard solder is melted on the target face, then a sheet of pure iron 2 mm thick is pressed on and the whole cooled.
$\text{Fe}^{56}(\text{d}, 2\text{n})\text{Co}^{56}$	19	2	b	0.2 (a)	
		5	c	0.5 (a)	
$\text{Fe}^{56}(\text{d}, \text{n})\text{Co}^{57}$	11	5	c	3.0 (b)	
$\text{Ni}^{60}(\text{p}, \alpha)\text{Co}^{57}$	9	2	a	0.5 (b)	As for iron targets (see above) but using nickel sheet.
$\text{Zn}^{66}(\text{d}, 2\text{n})\text{Ga}^{66}$	19	1	a	10 (b)	Pure zinc is melted on the target head, then machined smooth.
$\text{Ge}^{74}(\text{d}, 2\text{n})\text{As}^{74}$	19	1.5	b	0.25 (b)	Germanium is crushed and the powder stirred with molten "Easiflo". The mixture is pressed on to the target head.
$\text{Ag}^{109}(\text{d}, 2\text{n})\text{Cd}^{109}$	19	2	a	0.2 (c)	Silver sheet soldered on with soft (Pb-Sn) solder.
$\text{Cd}^{112}(\alpha, 3\text{n})\text{Sn}^{113}$	39	1	a, b	0.2 (c)	Cadmium sheet soldered on with soft (Pb-Sn) solder.
$\text{Sb}^{121}(\alpha, \text{n})\text{I}^{124}$	39	1	b	0.003 (c)	Antimony melted on target head, then machined smooth.
$\text{Ta}^{121}(\text{d}, 2\text{n})\text{W}^{181}$	19	1.8	b	0.15 (c)	Tantalum foil spot-welded to nickel sheet and this hard-soldered to target head.
$\text{Pt}^{195}(\text{d}, 2\text{n})\text{Au}^{195}$	19	2	a	0.5 (c)	Platinum hard-soldered to target head.
$\text{Pb}^{206}(\text{d}, 2\text{n})\text{Bi}^{206}$	19	1.5	b	5.0 (b)	Lead melted on target head then machined smooth.

(a) The yield figures are well established and are reproducible on a routine basis.

(b) The yield represents an average value taken over many individual bombardments.

(c) Yield is estimated only roughly, as means of taking accurate measurements not available.

copper blocks of different sizes, to which on the shaded face (but not extending quite to the edges) are attached the materials forming the actual target. Table 1 gives a list of target materials, isotopes produced, maximum power, and the preferred means of bonding the target material. Fig. 1(d) shows a circular target whose front face is

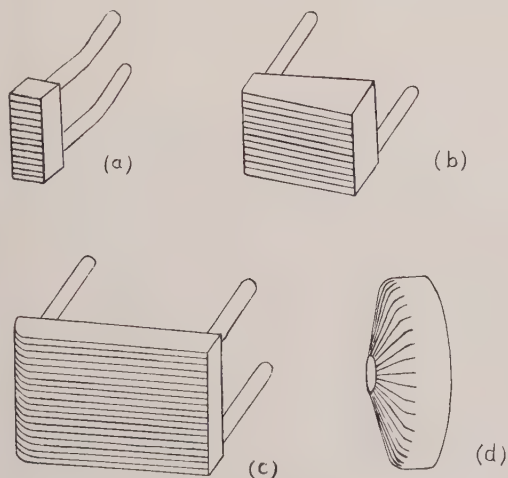


Fig. 1. Internal cyclotron targets. The cyclotron beam impinges at a glancing angle on the faces distinguished by shading. Dimensions of target faces are: (a) $2'' \times \frac{3}{4}''$, (b) $2'' \times 1\frac{1}{2}''$, (c) $3'' \times 2''$, (d) conical surface with semi-angle 80° outer diameter $3''$.

bevelled at 10° . Such targets have been fabricated from several metals but are used regularly only for the production of Na^{22} through the reaction $\text{Mg}^{24}(\alpha, n)\text{Na}^{22}$. The target material is a Mg-Al alloy containing 6% of aluminium. The rear face of the target (not shown in the figure) is cut away to form a circular channel for cooling-water: during bombardment the disc is clamped to a circular head fitted with pipes carrying the water supply. The disc rotates in the machine at 170 r.p.m. while the neutrons are incident on the bevelled face. Power dissipation is about 4 kW.

Several desirable target materials, e.g. rubidium, from which Sr^{85} can be made by the reaction $\text{Rb}^{85}(d, 2n)\text{Sr}^{85}$, have properties such as volatility and chemical reactivity which preclude the application of the above techniques. Chemically stable and involatile compounds must therefore be used instead of the pure element; of these compounds very few are suitable for internal bombardment

because of their poor thermal conductivity and difficulty of attachment to the target block. Some progress has been made in pressing materials such as halogen salts, oxides, or carbonates of reactive metals into grooves or shallow slots in copper blocks and covering them with a thin copper or aluminium foil. "Powder" targets of this nature, however, will withstand much less intense beams than purely metallic ones, before perforation of the cover foil occurs with consequent loss of the target material. Better results are generally obtained by bombarding powders in a special capsule illustrated in fig. 2, in the exit port of the cyclotron. The target consists of a semi-cylindrical water-cooled copper block fitted into the end of a "Tufnol" tube $1\frac{1}{2}''$ in diameter. As shown in fig. 2 an oval depression is formed in the flat face of the block. Into this is pressed the target powder, which is held in place by a 0.001" copper foil clamped on by the masking plate. The copper foil is air-cooled by compressed air from the pipe shown just to the right of the oval depression.

It is generally convenient if enough target material is available to make the target "thick", that is to say, of thickness comparable with the range of the bombarding particles in it. This means that particles of all energies from zero to the maximum

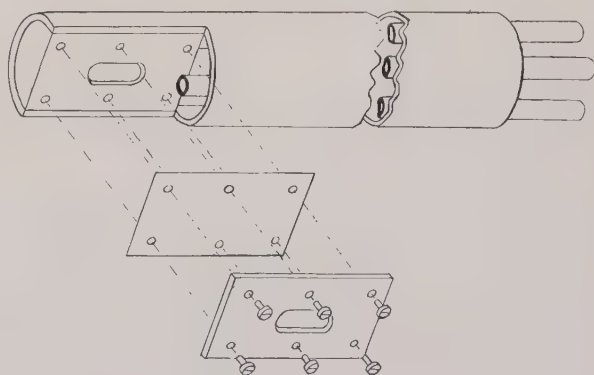


Fig. 2. Exploded view of external target, showing oval "slot" depression for powdery materials, and cover foil clamped in position by masking plate. A typical slot may measure $\frac{1}{2}'' \times \frac{1}{4}'' \times \frac{1}{16}''$.

available are present at different points. In order to avoid the production of unwanted isotopes by side reactions, it may be necessary to use bombarding particles in a narrow range of energy. This is often

feasible with a metal target which can be used in the form of a thin foil but may be impossibly difficult if a loose powder has to be bombarded. It should be noted that accelerated ions in the exit port are necessarily at nearly the full energy available; lower energies on the target can be got only by covering it with the appropriate thickness of absorbing material.

The magnitude of the activities which are developed in targets varies a great deal and may amount to several curies (gamma ray equivalent of radium) on an internal target. In practice much of this is short-lived unwanted activity formed by a side reaction for example, $\text{Mg}^{26}(\text{d}, \alpha)\text{Na}^{24}$ in magnesium targets used for production of sodium-22, and can be allowed to die away before any target

processing is begun. Nevertheless some hundreds of millicuries may have to be handled on an internal target and perhaps ten millicuries on an external target. The radiation hazards in processing on a routine basis are therefore quite considerable, and the techniques that have been developed for the safe handling of targets are the subject of Part II of this paper.

Acknowledgements

The authors wish to thank the many people who have contributed ideas on target preparation. The fabrication of targets is now largely in the hands of Mr. F. Buswell. We are glad to acknowledge the co-operation of the Radiochemical Centre, Amersham in the measurement of some target yields.

ISOTOPE PRODUCTION WITH THE NUFFIELD 60-INCH CYCLOTRON

Part 2

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A machine has been developed for handling "internal" targets from the 60-inch cyclotron by remote control in a lead-shielded box. The machine is regularly used to shave active materials

from metallic targets, and delivers the shavings into a standard isotope can, ready for transport. "External" targets of powdery non-metallic materials are handled in a shielded glove-box.

1. Introduction

In Part 1 of this paper it was pointed out that radioactive substances produced in the Nuffield cyclotron are of two general types; (a) "internal" targets, which are metallic blocks or thin strips of metal bonded to a base block of copper (b) "external" targets which are non-metallic powders enclosed in a copper capsule. It is only rarely that such targets are in a form suitable for direct use by the experimenter, who usually requires the active material to be removed from its support, and may require it to undergo chemical treatment. Removal of the activity by chemical means (etching) is sometimes convenient, but not in general so because it is slow and because it gives a solution of the wanted activity from which solid sources may or may not be easy to prepare if required. Furthermore the etching often leads to contamination of the desired activity by products from the supporting material; subsequent chemical operations are thus rendered more hazardous than need be and more complicated because of decontamination problems. It is therefore preferable to separate the desired activity from targets as a first step by purely mechanical means, whether subsequent chemical treatment is contemplated or not.

2.2. Handling of "Internal" Targets

We have developed a device based on an "ATLAS" seven-inch shaping machine which is operated entirely from behind lead shielding walls. Internal targets are positioned in the machine in

special vices, and shavings of active material formed by the cutting action of the machine are collected in standard isotope cans which are sealed and delivered into a lead container for transport. A brief description of the machine and its operation follows with reference to fig. 3, 4, 5.

Fig. 3 shows a view of the shielded box. A perspex box approximately 2'8" $\times$ 2'0" $\times$ 3'8" encloses the machine itself, which stands on a steel table. The table top is formed by a steel tray holding a 2" depth of lead, and the perspex box is lined on the outside with lead blocks giving a 4" thickness on the side shown and 2" elsewhere. The top of the box is in two parts forming a double sliding door; this has no lead shielding.

The front wall of the box is pierced by a hollow perspex window A containing a 4" thickness of zinc bromide solution. The window is hinged at one side and can be opened to give direct access through a small sliding perspex door, to the shaping machine within. Also piercing the box are remote control tongs B and various handles C₁, C₂, etc. which control through Bourdon cables or direct mechanical links the various moving parts and adjustments of the machine.

At the back of the box (not shown) there is another window which is used for insertion of the target, and a device for screwing caps on to the isotope cans and delivering them out into lead containers. A sectional drawing of this "posting box" is shown in fig. 4.

A simplified view of the whole assembly as it would appear with the front wall removed is

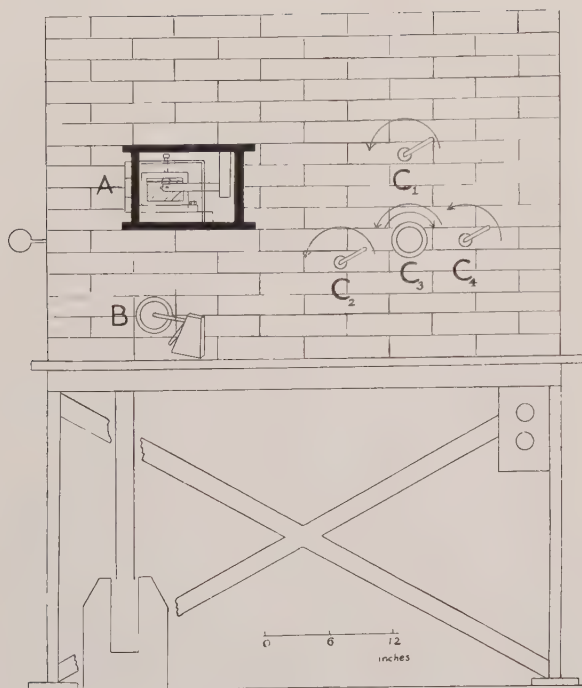


Fig. 3. External view of target handling box. The handles C_1 , C_2 , C_3 , C_4 , control respectively: C_1 —vertical movement of cutting tool through screw N (fig. 5); C_2 —backward and forward motion of the shaping machine table, F, through screw M (fig. 5); C_3 —range of oscillation of the ram movement from side to side, through screws I (fig. 5); C_4 —handwheel J (fig. 5), six rotations of which causes the ram and cutter to make one complete oscillation.

presented in fig. 5. Some details are omitted and others enlarged above their real relative size for the sake of clarity.

In accordance with the type of target (fig. 1(a), 1(b), or 1(c)) a special vice E is selected and bolted to the table of the machine F. Corresponding to the vice a perspex hopper G is then fitted to the table, care being taken that a dummy inactive target H, when fitted into the vice, projects about $\frac{1}{8}$ " into the hopper through a close-fitting slot. In order to facilitate the exact positioning of active targets in the vice, each is made with a groove milled in the lower edge, which fits over a lip formed in the base-plate of the vice. The controls I of the machine are then adjusted so that on rotating the hand-wheel J the cutter K will just traverse the dummy target from side to side. An isotope can is then put in position at the base of the hopper and the dummy removed. The active target is then quickly positioned in the vice by means of long-handled tongs

through the rear window, and locked in place by a long box-spanner through the top of the box. All windows are finally closed, the motor L is started and cutting begun. The depth of cut can be regulated to about 0.001" by advancing the table of the machine (at right angles to the plane of the diagram) by turning the screw M. The cutter oscillates across the target face about once per second while being slowly raised or lowered by turning screw N. Thus the whole face of even the largest target can be traversed in about twenty minutes. When all the active material has been collected on the floor of the hopper it is swept aside by the rubber brush O and falls vertically down the very steep-sided funnel into the isotope can. The latter is then detached using the tongs B and delivered through the sliding port P in the back wall of the box into the postincubation box. After the cap is screwed on it falls through a rubber chute into a lead container for transport.

For the circular targets, shown in fig. 1(d), a vice would not be suitable. Instead they are screwed directly onto the spindle of an electric motor geared to rotate once in five minutes. The motor assembly is fixed to a base plate which is bolted to the table of the machine. The base plate is fitted with a swivel

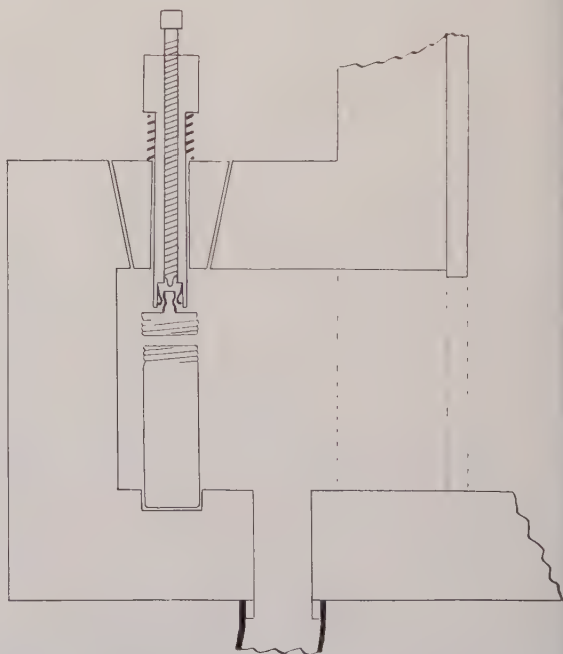


Fig. 4. Device for screwing caps on isotope cans, showing top view and side view. The opening to the right of the diagram corresponds with the port P in fig. 5.

that either the central circular face or the peripheral conical face of the target may be presented to the cutter. The cutting tool then makes about 300 oscillations along the radial section as the target revolves once.

It will be appreciated that the bar holding the cutting tool must work in a slot in the side of the spex hopper. We have not found it necessary to cover this with a sliding plate or flexible gland as the amount of shaved material escaping from the target is always negligibly small—far less than one part in ten thousand of the total target being machined. The hoppers are easily and completely decontaminated from tiny adhering fragments, after the main bulk of shavings have been posted out, by using a small camel-hair brush, and then the whole machine is decontaminated from the last traces of active material with a vacuum cleaner.

4. Handling of "External" Targets

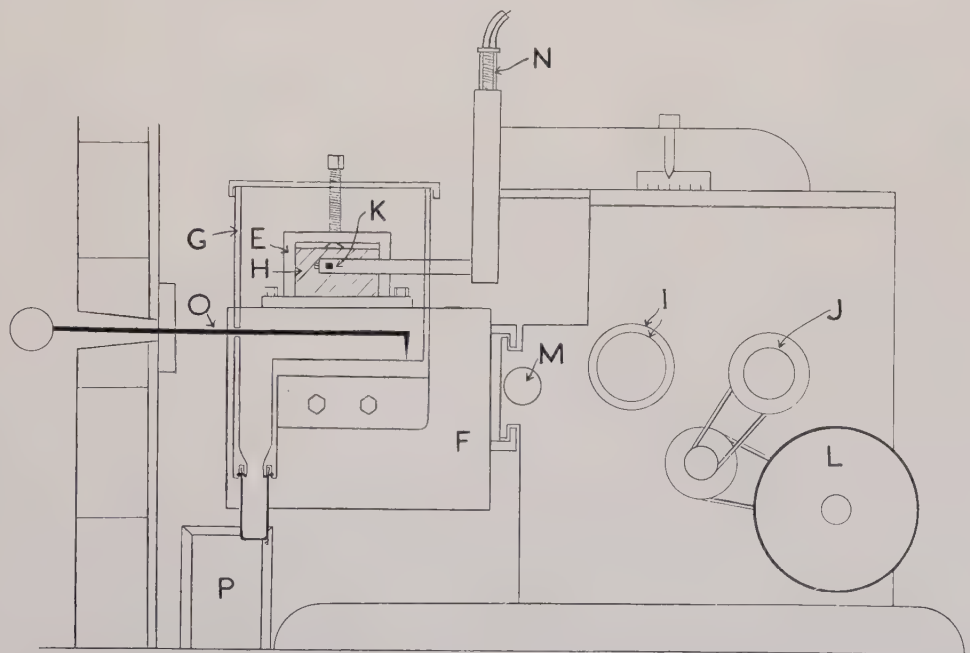
These targets are considerably less dangerous from the point of view of gamma radiation than the internally bombarded ones, but they need careful treatment as the material itself is often a loose powder and is easily airborne. As the demand for them is in fact rather small we have not developed an automatic device, but in principle the machine

described above could be modified to handle them. Instead we merely use a lead shielded glove-box. In this the target is held in a vice immediately above a funnel leading to a plastic bottle. The copper cover is cut with a scalpel and removed with tweezers. Active material is brushed out of the depression and into the bottle with a camel hair brush. The success of the operation depends very much on the skill of the operator who must clearly work at speed and be ready with various extra tools in case of unexpected circumstances—such as that the powder may all have sintered firmly to the copper cover foil. We feel that if the demand for this type of target increases we shall have to abandon our present methods and develop remotely controlled devices. These will have to be capable of very fine control over a great variety of operations.

Acknowledgements

The early part of the machine development was done by Mr. J. Strong; we should like to thank Mr. N. Clarke and Mr. H. Hayward of the Physics Department Workshop staff who very painstakingly built the various components.

The original suggestion of using an "ATLAS" shaping machine came from Mr. J. Marriott of A.W.R.E., Aldermaston.



5. Idealised view of shaping machine with lead walls removed. Unimportant details of the machine are omitted and the target itself, H, vice E, hopper G and machine table F are exaggerated in relative size.

ANALYSE BI-DIMENSIONNELLE DU TEMPS DE VOL DE NEUTRONS DE QUELQUES DIZAINES DE keV ET DE L'ENERGIE DES γ EMIS EN COÏNCIDENCE

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The simultaneous recording of two phenomena in a magnetic tape makes possible:

1. the study of the gamma-rays emitted by an excited nucleus produced by neutron emission near threshold;

2. a better separation by time of flight of the neutrons corresponding to different neighbouring excited states and the measurement of the variation of the cross-section in a small energy interval.

Un noyau étant formé par émission de neutrons, il est facile de sélectionner, par temps de vol, les neutrons correspondant à un état excité du noyau résiduel près de son seuil de production.

Un enregistreur à deux voies de 63 canaux¹⁾ reçoit d'une part le spectre d'amplitude d'un compteur γ (gros cristal NaI(Tl)[†] associé à un photomultiplicateur 58 AVP ou RCA 7046), d'autre part le retard des impulsions d'un compteur de neutrons parvenant à un convertisseur de temps en amplitude après une impulsion du compteur γ , dans un délai voisin de 150 ns. Le détecteur de neutrons est une boîte de bore-10 (10 cm de diamètre, 2 cm d'épaisseur), associée à un cristal de NaI(Tl) de 1" d'épaisseur et à un photomultiplicateur RCA 7046. Les conditions simultanées d'enregistrement sont: une coïncidence dans le délai de 150 ns (discriminateur connecté en parallèle à la sortie du convertisseur, ou circuit de coïncidence connecté en parallèle à ses entrées), le signal d'un sélecteur à 1 canal sélectionnant 480 keV sur le détecteur de neutrons, et accessoirement un discriminateur en parallèle sur le compteur γ . Le convertisseur était soit une bascule déjà décrite²⁾, soit un circuit fondé sur l'addition de courants dans une diode tunnel.

Après enregistrement codé des deux spectres sur

une bande magnétique, chacun d'eux pouvait être relu après coup, moyennant une condition imposée à l'autre.

Les figures 1 et 2 représentent une partie des résultats de mesures préliminaires sur la réaction $V(p, n)$, étudiée par ailleurs³⁾. L'énergie de neutrons de quelques dizaines de keV pouvant être facilement mesurée à quelques keV près, nous avons étalonné le Van de Graaff par ce moyen, utilisant les seuils de la réaction $V(p, n)$, comparés avec une précision de 10 keV⁴⁾.

La sélection des γ provenant d'un niveau noyau résiduel fait apparaître des γ de 750 keV environ dans le rayonnement du niveau "1486 keV" ce qui serait en accord avec une transition entre les états "1486" et "1350", signalée comme possible.

Quelques lectures du spectre de temps conditionné par diverses régions du spectre γ suggèrent d'une façon non concluante, le dédoublement du niveau "1486 keV".

Les premières mesures (dont celles des figures

* Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, (Brésil).

† Le détecteur, prévu pour l'étude ultérieure de γ énergiques, a une assez mauvaise résolution en énergie.

¹⁾ A. Pagès, Colloque International sur l'électronique nucléaire, Paris, 1958, 283; J. Phys. **21** (1960) 475.

²⁾ R. Balliniet E. Pomelas, Nucl. Instr. and Meth. **11** (1961) 331.

³⁾ Y. Cassagnou, J. M. F. Jeronymo, C. Levi, L. Papineau, D. Stanojevic, Colloque de la Sté Française de Physique, Strasbourg, 1961; J. Phys. Radium **22** (1961) 604.

Communication présentée au Rutherford Jubilee International Conference, Manchester 1961.

⁴⁾ A. T. G. Ferguson et E. B. Paul, Nucl. Phys. **12** (1959) 331.

⁵⁾ B. Lobkowicz et P. Marmier, Helv. Phys. Acta **34** (1961) 85.

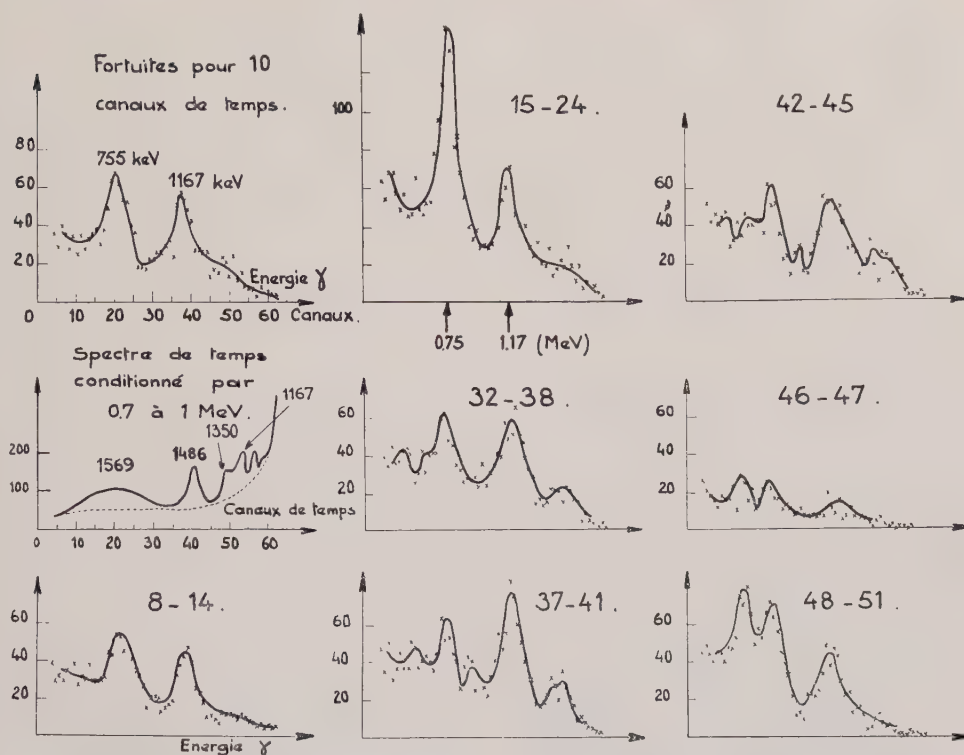


Fig. 1. Spectre de temps de vol obtenu avec des protons de 3.165 MeV. Spectres γ conditionnés par les canaux du spectre de temps notés sur chaque graphique. Les "fortuites" sont déterminées par une mesure sans écran de bore. Base de temps = 24.7 cm.

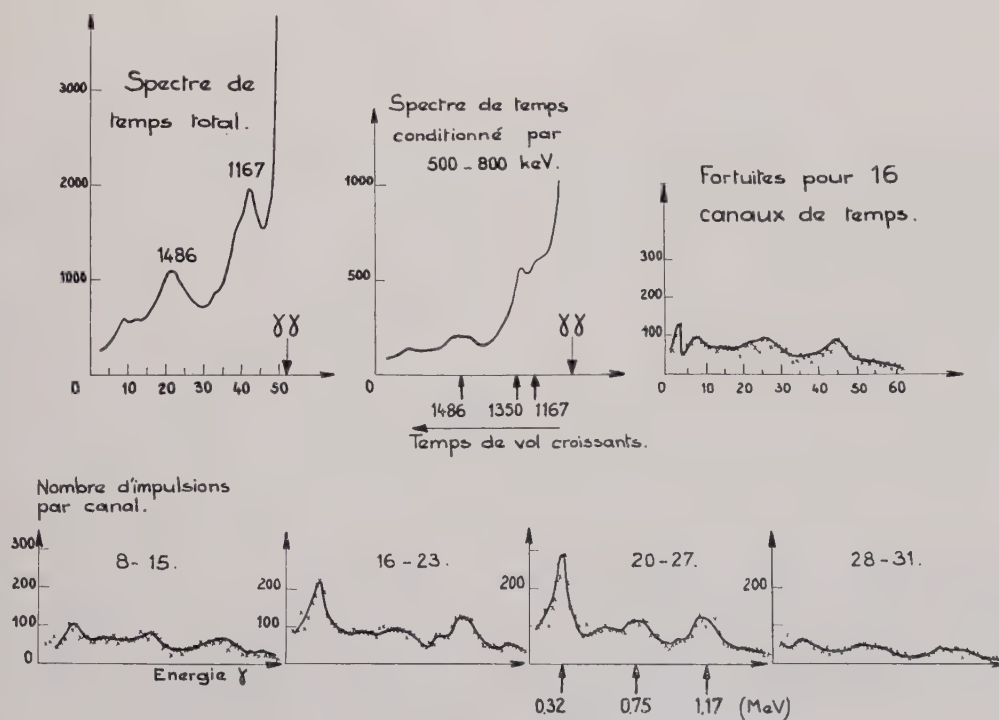


Fig. 2. Spectres obtenus avec des protons de 3.08 MeV. Base de temps = 15 cm.

et 2) étaient perturbées par la diffusion inélastique de neutrons énergiques par le cristal du compteur γ , et détection ultérieure par le compteur de neutrons: nous avons adopté par la suite une géométrie de nature à faciliter l'élimination de ces neutrons parasites par temps de vol.

D'un emploi plus difficile que si on avait affaire à des particules chargées détectées par jonction, cette méthode d'étude des niveaux du noyau résiduel ne semble pas devoir se suffire à elle-même avec des neutrons: mais elle est à employer conjointement aux mesures de coïncidences $\gamma\gamma$, soit pour contrôler

soit pour suggérer des mesures à plus haute énergie avec une meilleure statistique.

La sélection par temps de vol a également permis d'étudier, dans deux régions d'énergie restreintes, la variation de section efficace de quelques niveaux (figure 3). Les corrections d'efficacité de détection n'ont pas été faites. La "lecture conditionnée" joue ici un rôle accessoire, permettant de mieux séparer certains groupes de neutrons: cette méthode peut ainsi être utilisée en concurrence avec un faisceau pulsé, pour étudier des réactions où sont émis des neutrons de faible énergie.

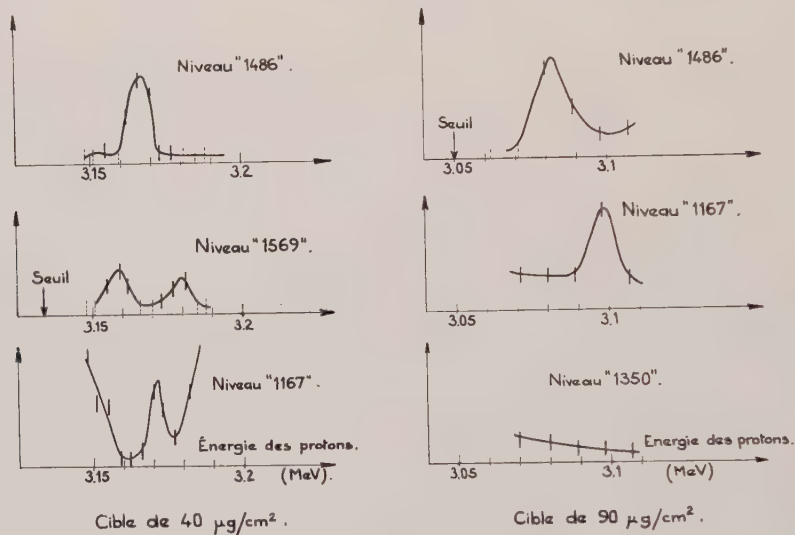


Fig. 3. Variation d'intensité de plusieurs groupes de neutrons de la réaction $V(p, n)$ avec l'énergie des protons incidents (les courbes ne sont pas normalisées les unes par rapport aux autres). Lecture "non conditionnée" pour le groupe "1486", conditionnée par la région convenable d'énergie γ pour les autres.

EXPERIMENTAL STUDY OF THE INFLUENCE OF NON-PROPORTIONAL RESPONSE OF NaI(Tl) SCINTILLATION CRYSTALS UPON THE ENERGY RESOLUTION FOR GAMMA RAYS†

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resolution of a summing Compton spectrometer has been accurately measured for several gamma ray energies. In the events detected, only one Compton scattering takes place in the first crystal. Thus for the part of the energy which is released in the first crystal, the contribution to the line width arising otherwise from a varying number of Compton interactions and non-proportional response of the scintillator is not

present. This contribution has been evaluated by comparing, for each energy, the resolution of the summing Compton spectrometer with the resolution expected if the total energy were shared by the two crystals in the same ratio, but multiple scattering were present in both of them. The results are discussed and yield fairly good agreement when compared with theoretical expectations.

Introduction

Considerable deviations from proportional response to gamma rays in NaI(Tl) scintillators have been observed for a long time¹) and recently they have been accurately remeasured^{2,3}). In order to account for this behaviour it is inferred that the scintillation efficiency (amount of light produced per unit energy) of the electrons which finally transfer the energy to the crystal is not a constant but a function of their energy. The number of these electrons and the way in which energy is shared among them varies statistically for monochromatic gamma rays totally absorbed in the crystal. Therefore fluctuations in the overall scintillation efficiency for gamma rays must be expected and they will contribute to the broadening of the full energy gamma peak measured with scintillation spectrometers. Recently P. Iredale⁴) and C. D. Zerby *et al.*⁵), performed calculations in order to estimate the contribution for NaI(Tl) crystals, 1½ in. dia. × 2 in. high and 2½ in. dia. × 2 in. high, respectively. In both cases it is concluded that the contribution must be fairly large, especially for energies below 1 MeV. Therefore it seemed to be important to

devise an experiment which would allow evaluation of this contribution and its comparison with the theoretical expectations.

2. Experimental Possibilities

There seem to be two possible approaches to the experimental study of the contribution of the non-proportional response to the intrinsic resolution of scintillators:

(a) As pointed out by Iredale⁴), one could attempt to determine how the resolution is affected by varying the degree of non-proportionality of the scintillator. This could be achieved either by growing crystals under different conditions or by taking advantage of a possible temperature dependence of the non-proportionality⁶).

(b) Even if the degree of non-proportionality is kept constant, a measurement can be performed in which its contribution to the intrinsic resolution is altered by varying in a known way the statistical distribution of the electrons which finally interact with the crystal. One possibility for this would be

¹) D. Engelheimer, *Rev. Sci. Instr.* **27** (1956) 589.

²) J. Kantele and R. W. Fink (private communication).

³) P. Iredale, *Nucl. Instr. and Meth.* **11** (1961) 336.

⁴) P. Iredale, *Nucl. Instr. and Meth.* **11** (1961) 340.

⁵) C. D. Zerby, A. Meyer and R. B. Murray, *Nucl. Instr. and Meth.* **12** (1961) 115.

⁶) E. der Mateosian, M. McKeown and C. O. Muehlhause, *Phys. Rev.* **101** (1956) 967.

† A preliminary report of this work was presented at the Symposium on Nuclear Instruments, Harwell, England, September 11-13, 1961, and will be published in the Proceedings of this symposium.

†† On leave of absence from Instituto de Fisica, Bariloche, Argentina.

to study the response of NaI(Tl) crystals to monoenergetic electrons. The broadening of gamma ray full energy peaks due to multiple Compton interactions followed by a photo-process would thus be eliminated. However, even monoenergetic electrons impinging on the crystal will produce secondary electrons (δ -electrons) fluctuating in number and energy. This will still result in a broadening of the peak due to non-proportionality. According to Iredale⁴), this last contribution can be treated independently from the effect due to the fluctuating number of Compton- and photo-electrons.

A second possibility is to generate single primary electrons inside the scintillator by allowing gamma rays to be scattered by a single Compton process in the investigated crystal and by detecting the scattered photon in a second detector. This approach was adopted for the present work. The fluctuations in the scintillation efficiency due to the statistical distribution of Compton- and photo-electrons in the first crystal are again eliminated, whereas the contribution due to δ -electrons is still present.

3. Measurement of the Non-Proportionality

Some differences in the non-proportionality of response to gamma rays have been found in a comparison of several crystals³). It was therefore necessary to determine the deviations from proportionality for the scintillator actually used in the present work (crystal 1; cf. fig. 2). This was a $1\frac{1}{4}$ in. dia. $\times$ 2 in. high NaI(Tl) Harshaw crystal mounted on a 6342A RCA photomultiplier tube, the pulses from which were fed to a 400-channel pulse height analyzer. A calibration of the analyzer was performed by means of a highly accurate and stable mercury pulse generator. The pulses from this generator were given the same shape as the pulses from the detector with an RC shaping network. The positions of several photopeaks corresponding to gamma rays of accurately known energies ranging from 46 keV to 1.33 MeV were then carefully determined. One of them was taken as a reference to check the stability of the system and its position was determined before and after each measurement. The radiation from the sources was

collimated in such a way that it impinged on the same region of the crystal as in the main experiment. The results obtained are shown in fig. 1.

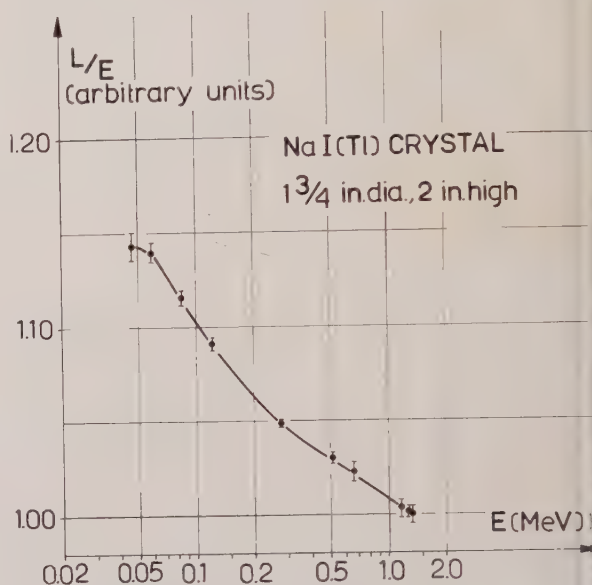


Fig. 1. Scintillation efficiency L/E (L , light output; E , energy of the gamma ray) determined for different gamma ray energies.

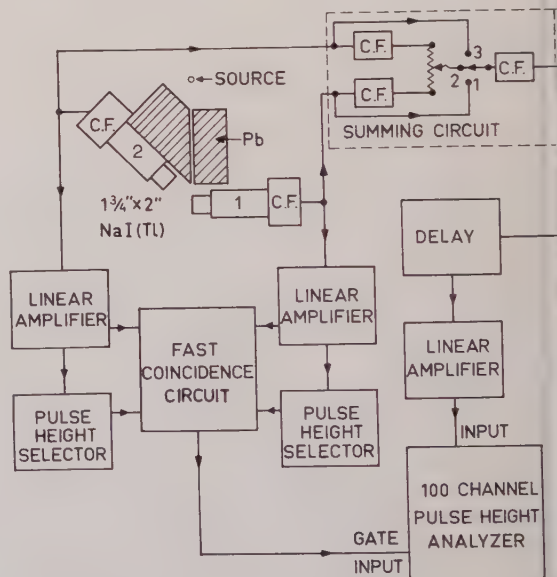


Fig. 2. Detector-source arrangement and block diagram of the summing Compton spectrometer used for the present experiments. The pulse height selector in channel 2 was adjusted in each case to accept pulses equal to, or larger than those corresponding to single Compton scattering in crystal 1. Positions 1 and 3 of the switch in the summing circuit have been used when recording the spectra corresponding to the part of the total energy released in crystals 1 and 2, respectively.

Experimental Set-Up for Determining the Influence of the Non-Proportionality upon the Resolution

The arrangement used is similar to the summing Compton spectrometer described by H. Takekoshi⁷⁾. The geometry of source and detectors as well as the block diagram of the electronic circuits used are shown in fig. 2.

The gamma rays from the source were collimated between two parallel lead walls, about 3 mm apart. The radiation impinged upon the uppermost layer of crystal 1 (cf. fig. 2) and was scattered from crystal 1 to crystal 2. The resulting pulses are summed and recorded in a 100-channel pulse height analyzer, gated by the output pulses from a fast coincidence circuit. Two $1\frac{3}{4}$ in. dia. $\times$ 2 in. high NaI(Tl) crystals mounted on 6342A RCA photomultipliers were used. For a given gamma ray energy E_0 , the scintillation in crystal 1 is due to a single Compton electron of energy E_1 . The remaining energy E_2 may be totally absorbed in crystal 2 in the usual way, i.e. by direct photo-absorption or by Compton processes followed by photo-absorption. Matching the amplifications in the two channels it is possible to obtain spectra, which, with a convenient discriminator setting in channel 2, present full energy peaks of the measured gamma rays, while the Compton distributions are eliminated to a large extent.

The width of each of these peaks results from contributions of both detectors. The contribution of detector 2 includes the effect of statistical fluctuations in the number and energy of the primary electrons which produce the scintillation. On the other hand, the contribution of detector 1 does not include this effect because only one primary electron per event is released in this crystal. Since a large scattering angle and a small solid angle for crystal 2 have been chosen (cf. fig. 2) the energy of these electrons is fairly constant. Thus the resolution obtained should be better than that obtained by adding pulses from two coincident gamma rays of energies E_1 and E_2 recorded in detectors 1 and 2, respectively. By studying experimentally this difference, it is possible to obtain information regarding the influence of non-proportional response upon resolution.

5. Treatment of the Data

The general expression given by E. Breitenberger⁸⁾ for the resolution of a scintillation detector to a good approximation can be written as

$$R^2(E) = \alpha + \frac{\beta}{E} + F(E). \quad (1)$$

Here $R(E)$ is the relative half width of the photo-peak corresponding to a gamma ray energy E , α is the term accounting for the variance of the probability of light transfer for individual scintillations, β/E accounts for the statistical nature of the production and multiplication of electrons in the photomultiplier tube and $F(E)$ accounts for a possible non-normal variance in the statistical distribution of the total number of light quanta produced at each scintillation. The non-proportional response of the crystal to electrons will certainly give rise to a supranormal variance, thus yielding a positive value for $F(E)$. The contributions to the resolution from the δ -electrons and from the multiple Compton scattering (if present) can be assumed to be independent of each other⁴⁾. Accordingly, it is justified to write

$$F(E) = F^\delta(E) + F^c(E)$$

It is now possible to derive the expression for the total line width $\Gamma_0(E_0)$ obtained with the summing Compton scintillation spectrometer, if Gaussian line shapes are assumed. Supposing that a constant energy E_1 is released in the first crystal and the rest, $E_2 = E_0 - E_1$, in the second, the following expression is obtained:

$$\Gamma_0^2(E_0) = \left[\alpha_1 + \frac{\beta_1}{E_1} + F_1^\delta(E_1) \right] \cdot E_1^2 + \left[\alpha_2 + \frac{\beta_2}{E_2} + F_2^\delta(E_2) + F_2^c(E_2) \right] \cdot E_2^2. \quad (2)$$

Due to the characteristics of the experiment, the multiple Compton scattering term of crystal 1 is not present.

For the total line widths of single gamma ray

⁷⁾ H. Takekoshi, Rev. Sci. Instr. **31** (1960) 1280.

⁸⁾ E. Breitenberger, Progr. Nucl. Phys. **4**, edited by O. R. Frisch (Pergamon Press, London and New York) 1955, p. 56.

peaks of energies E_1 and E_2 in crystals 1 and 2, respectively, the following expressions hold:

$$\Gamma_1^2(E_1) = \left[\alpha'_1 + \frac{\beta_1}{E_1} + F_1^d(E_1) + F_1^c(E_1) \right] \cdot E_1^2 \quad (3)$$

$$\Gamma_2^2(E_2) = \left[\alpha_2 + \frac{\beta_2}{E_2} + F_2^d(E_2) + F_2^c(E_2) \right] \cdot E_2^2 \quad (4)$$

In formula (3) α'_1 has been introduced instead of α_1 in order to account for the change in the variance of the probability of light transfer, discussed by Bisi and Zappa⁹). α'_1 corresponds to the case where a gamma ray interacts with the crystal by multiple processes, and is smaller than α_1 , which corresponds to the case where a gamma ray releases a single primary electron.

From formulae (2), (3) and (4) the following expression results

$$\frac{\Gamma_1^2(E_1) + \Gamma_2^2(E_2) - \Gamma_0^2(E_0)}{E_1^2} = F_1^c(E_1) - (\alpha_1 - \alpha'_1) \quad (5)$$

With the geometry used, the overall influence of fluctuations in E_1 (and E_2) was estimated to be fairly small. Thus E_1 and E_2 were replaced by the mean values $\bar{E}_1$ and $\bar{E}_2$ obtained by averaging over the possible angles.

The variance of the probability of light transfer in the region used of crystal 1 has been determined experimentally in order to estimate the difference $(\alpha_1 - \alpha'_1)$. A collimated beam (ca. 2 mm in diameter) of the 122 keV gamma rays from the decay of Co^{57} was used. The beam was successively aimed at different points of the upper surface and side of the crystal and the position of the photopeak was recorded in each case. The maximum difference observed was 1% and the standard deviation was 0.33%, which corresponds to a half-width of 7.8×10^{-3} . Thus a value of $\alpha_1 = 6 \times 10^{-5}$ is obtained. The difference $(\alpha_1 - \alpha'_1)$ is still smaller and has therefore been neglected. Thus formula (5) can be rewritten as:

$$F_1^c(\bar{E}_1) = \frac{\Gamma_1^2(\bar{E}_1) + \Gamma_2^2(\bar{E}_2) - \Gamma_0^2(E_0)}{\bar{E}_1^2} \quad (6)$$

It is seen from formula (6) that the contribution to the square of the resolution (R^2) due to multiple Compton scattering and non-proportional response

⁹) A. Bisi and L. Zappa, Nucl. Instr. 3 (1958) 17.

in the first crystal can be determined for the energy $\bar{E}_1$. For this purpose the resolution of the summing Compton spectrometer and of detectors 1 and 2 must be determined for energies E_0 , $\bar{E}_1$ and $\bar{E}_2$, respectively. The resolution of the summing Compton spectrometer is measured directly and the single resolutions can be obtained if one constructs the curve of the resolution vs. the energy of each detector and reads off the values corresponding to $\bar{E}_1$ and $\bar{E}_2$.

6. Experimental Results

The following gamma ray energies were used in the measurements:

Co^{57}	122 keV
Hg^{203}	279 keV
Na^{22}	511 keV, 1276 keV
Cs^{137}	662 keV
Co^{60}	1173 keV, 1333 keV

The values of the resolution measured in the summing Compton spectrometer for the five underlined gamma ray energies above are shown in figure 3. Great care has been taken to make sure that no undesired influence upon the line widths arose from the pulse discrimination performed in channels 1 and 2 (cf. fig. 2). This was done by measuring the resolutions for different discriminator settings where no such influence was found in the region of interest. The resolution curve obtained with the same geometry for single spectra recorded in detector 1 (cf. fig. 2) is also shown.

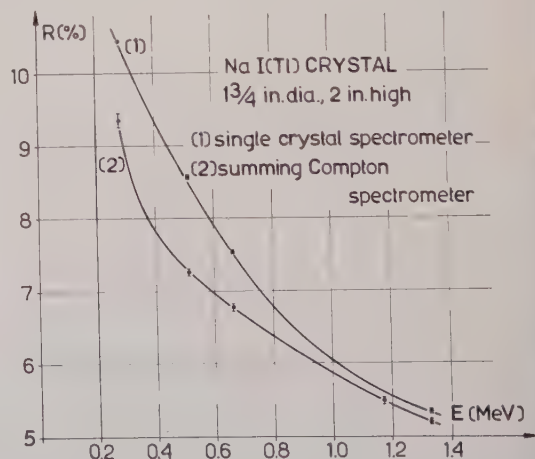


Fig. 3. Resolution vs. energy curves for: (1) single crystal spectrometer (detector 1), (2) summing Compton spectrometer.

It is seen from fig. 3 that, in the energy region from 200 keV to about 1 MeV there is a considerable improvement in resolution when using the summing Compton spectrometer instead of the single crystal spectrometer. This improvement would have been still larger, if in the present arrangement the resolution of crystal 2 had not been considerably worse than the resolution of crystal 1.

It was of interest to study the contribution made by the term β_1/E_1 (cf. formula (3)) which arises from statistics in the production and multiplication of electrons in the photomultiplier of detector 1. This was done by letting light flashes from the screen of a Tektronix 585 oscilloscope fall onto the photocathode of photomultiplier 1, their intensity being reduced by a suitable filter (cf. refs.⁸ and ¹⁰). The light flashes were obtained by generating a sweep of 0.1 $\mu\text{sec}/\text{cm}$ with a frequency of 50 cps. The cathode ray tube screen was covered by a mask having a window about 1 cm wide. A cathode ray tube with a fast decaying phosphor was used and the beam was defocussed to avoid possible effects due to local irregularities of the screen. The resolutions corresponding to different energies were determined by changing the intensity of the oscilloscope beam. The result is plotted as a function of $1/E$ in fig. 4, together with the total resolution curve measured for detector 1. The long term

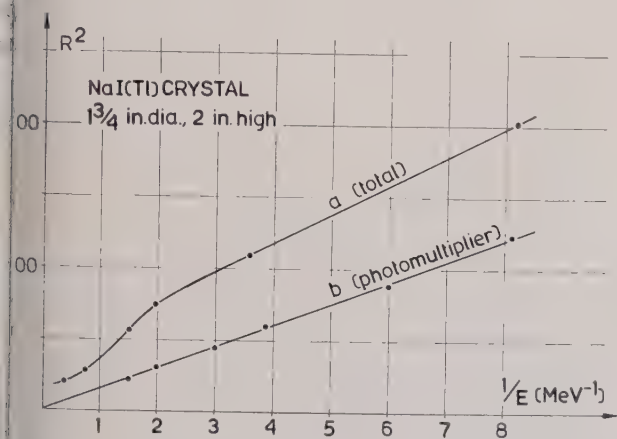


Fig. 4. (a) Square of the total resolution of detector 1 as a function of $1/E$, (b) contribution to curve (a) due to photomultiplier statistics.

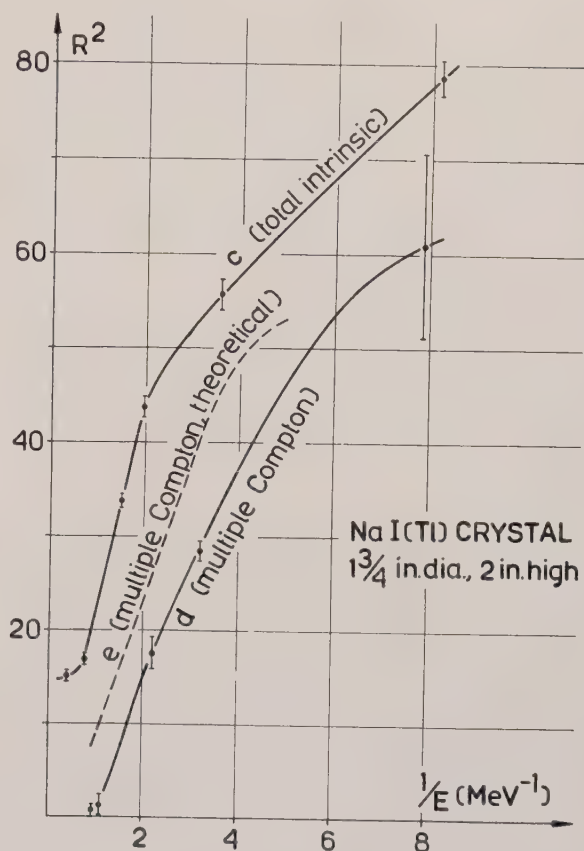


Fig. 5. (c) Square of the total intrinsic resolution of crystal 1, (d) experimentally determined contribution due to multiple Compton scattering and non-proportional response of the scintillator, (e) theoretical predictions by P. Iredale⁴ for the same contribution.

stability of the light intensity from the cathode ray tube was excellent and the fact that a straight line is obtained going through the origin, when plotting R^2 vs. $1/E$, indicates that there are no appreciable short term fluctuations present. Therefore the widths of the pulse height distributions obtained with these light flashes can be assumed to be exclusively due to photomultiplier statistics.

The experimental results of the multiple Compton scattering contribution computed by means of equation (6) are shown in fig. 5, curve (d). The values of the same contribution, calculated by Iredale⁴ (taken from curve (b) in his fig. 2) are shown in curve (e) for comparison. Iredale's calculations were performed for a crystal of a size somewhat different from the one used here. However, he points out that his calculations are not very

¹⁰ G. G. Kelley, P. R. Bell, R. C. Davis, and N. A. Lazer, *Nucleonics* 14, No. 4 (1956) 53.

sensitive to changes in the crystal size. Furthermore, the degree of non-proportionality of the crystal used in the present experiments is somewhat lower than that obtained by Iredale³) and used by him in his calculations⁴). Nevertheless this difference is very small in the region above 150 keV, and it is this region which is important in connection with the influence of multiple Compton scattering upon the resolution.

Curve (c) in fig. 5 shows the total contribution to R^2 arising from the crystal itself (total intrinsic resolution). It has been obtained by subtracting curve (b) from curve (a) of fig. 4.

7. Conclusions

The general agreement between the experimental values and Iredale's calculations must be regarded as surprisingly good. In fact the geometry used in the present experiment (cf. fig. 2) does not favour so much the assumptions made in those calculations. This, as well as the slightly higher degree of non-proportionality assumed for the calculations, could perhaps account for the somewhat lower

position of the experimental points. In any case it has been confirmed that the non-proportional response of NaI(Tl) crystals to electrons is responsible for a considerable part of their total intrinsic line width. It could even account for practically all the total intrinsic resolution, since the difference between curves (c) and (d) in fig. 5 is of the order of magnitude expected for the contribution due to δ -electrons⁴). However, no definite statement can be made on this last point because of the experimental errors and the uncertainties in the calculations.

Acknowledgements

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A LARGE APERTURE DETECTOR FOR SLOW POSITIVE IONS

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A detector is described in which slow positive ions are detected with uniform efficiency over an aperture 4 cm in diameter. It has a single stage box and grid type of electron multiplier, the secondary electrons from which are detected with a scintillation

counter. The background counting rate above a pulse amplitude at which 99% of ion pulses are registered is 0.3 counts per sec. The energy dependence of counting efficiency is also investigated.

Introduction

The detector described in this paper was developed as part of an apparatus to measure the electron-neutrino angular correlation in β decay of ^3H by a method involving detection of the recoil ions^{1,2}). The ions, which ranged in energy from 0 to 1500 eV and possessed a variety of positive charges, had to be detected over a large area of incidence with a uniformly high efficiency.

The usual technique for detecting slow heavy ions involves accelerating them on to the first dynode of an open ended electron multiplier tube^{3,4}). This kind of detector, whose signal to noise ratio enables one to measure particle rates as low as a few per sec with a detection efficiency approaching 100%, would have been adequate for this work but for its limited entrance aperture. This proved a severe handicap since the range of particle energies and their variety of charges precluded effective focussing of the beam. In a modification to the usual Allen type of multiplier introduced by Snell and Miller⁵), the first dynode was enlarged, providing an entrance aperture of 4×4 cm, and the secondary electrons from this were focussed on to a subsequent multiplying structure of more conventional dimensions. However, the sensitivity proved to vary widely with the point of incidence of particles on the enlarged electrode⁶), a fact probably associated with the critical nature of the focusing on to the second stage. The flexible geometry of scintillation counters suggests their possible application as wide aperture

ion detectors and their response to heavy ions has been investigated by Richards and Hays⁷). While electrons of 30 keV may be detected in this way, it appears that signals from individual heavy ions accelerated to the same energy are indistinguishable from photomultiplier noise pulses.

The detector finally developed for this work combines the open ended electron multiplier and scintillation detector techniques. Ions entering the detector are accelerated through a potential of some 11 kV onto a surface at which secondary electrons are produced. These are accelerated in turn through the same potential back to earth and crudely focussed onto the phosphor of a small scintillation detector. This technique takes advantage of the relatively large light output from electrons as compared with ions entering the phosphor and at the same time the focussing of secondary electrons from the large primary multiplying surface is uncritical. Moreover the exposure of only one multiplying surface when air is let into the vacuum system substantially reduces gain changes observed to occur in many-stage multipliers.

An early version of such a detector has been described by Ridley¹) in the context of an applica-

¹) B. W. Ridley, Nucl. Phys. **6** (1958) 34.

²) B. W. Ridley, Nucl. Phys. **25** (1961) 483.

³) J. S. Allen, Rev. Sci. Instr. **18** (1947) 739.

⁴) J. S. Allen, Proc. I.R.E. **38** (1950) 346.

⁵) A. H. Snell and L. C. Miller, A.E.C.D.-1956.

⁶) C. F. Barnett, O.R.N.L.-1669 (page 43).

⁷) P. I. Richards and E. E. Hays, Rev. Sci. Instr. **21** (1950) 99.

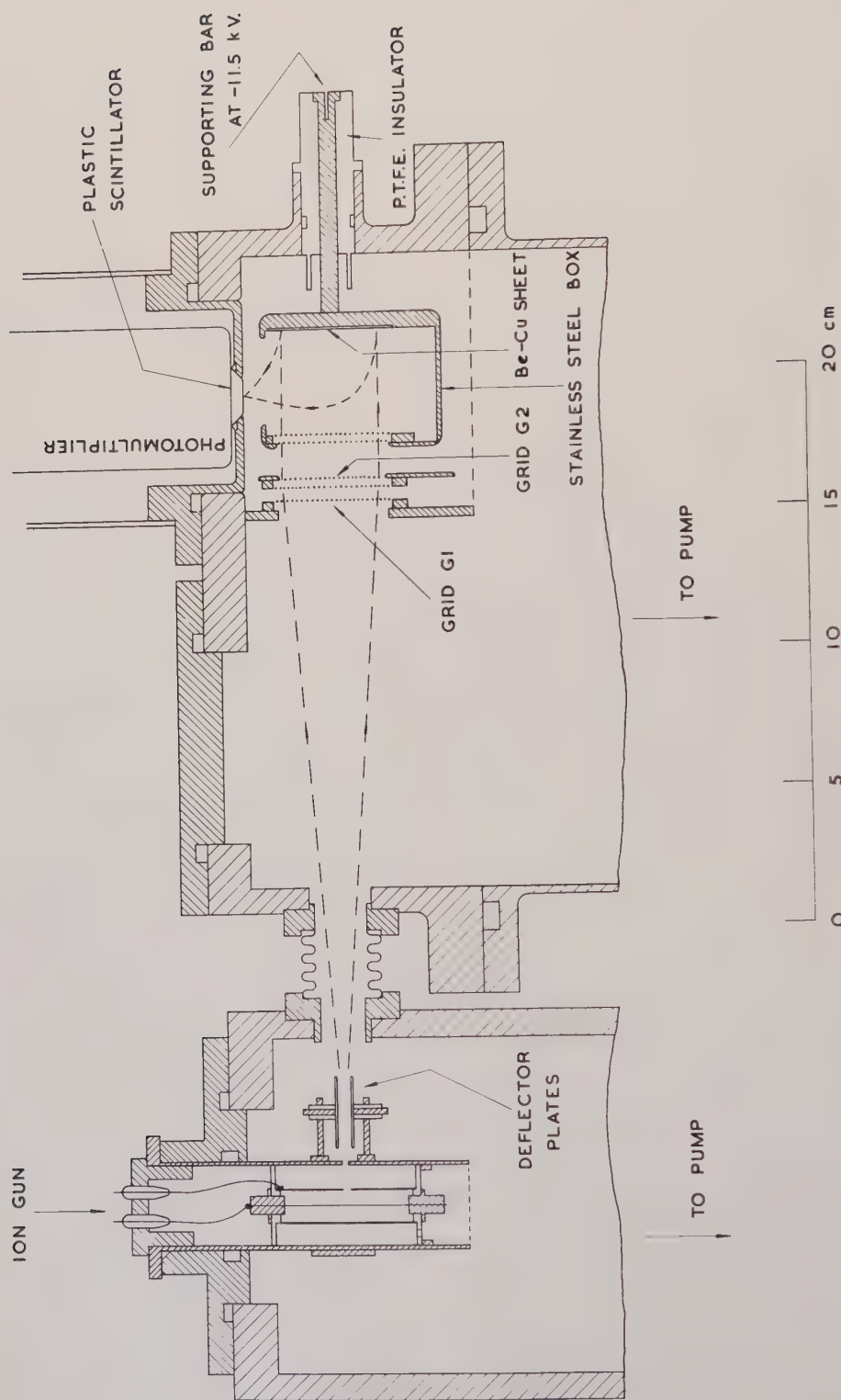


Fig. 1. Layout of ion detector and ion gun used for testing it.

on to the detection of recoil ions from decay of $^6\text{He}^{23}$, and a narrow beam ion detector employing the same principle has more recently been designed (by Daly⁸). An abbreviated account of the detector described below has already been given in a paper (on $^6\text{He}^{24}$ decay²), and the following account is intended to provide more detail than was then appropriate.

2. Description of Apparatus

The mechanical structure of the detector is shown in fig. 1. Its general form and dimensions are determined by the geometry of the recoil experiment and its detailed positioning so arranged as to bring secondary electrons from the primary multiplying surface to a focus on the scintillation detector. The part played by the detector in the complete apparatus is illustrated in fig. 1 of ref²).

Ions entering a 4 cm diameter circular aperture screened by the earthed grid G1 are accelerated between G2 and a gridded aperture in one face of a rectangular box maintained at a potential of -11.5 kV. The ions fall onto a sheet of surface oxidized Be-Cu alloy lining the rear face of the box, causing the emission of secondary electrons. These are extracted by a field penetrating through a hole in its roof and are accelerated onto a small piece of NE102 plastic scintillator. The electron trajectories indicated by dotted lines in fig. 1, are computed from potential distributions measured in a model of the detector in an electrolytic tank.

The phosphor is flashed with a layer of aluminium about $30 \mu\text{g}/\text{cm}^2$ in thickness and sealed into the wall of the vacuum system with cold setting Araldite in such a way that the aluminium layer makes electrical contact with the surrounding metal. The photomultiplier is a 13 stage EMI tube, type 9514, and is mounted outside the vacuum system. By operating it with potentials of 400 V/stage on the last three stages and 120 V/stage elsewhere, single ion pulses up to 30 V amplitude were obtained directly from the multiplier using only a cathode follower to drive the output.

The box itself is fabricated in stainless steel with a well polished exterior finish. It is supported by an arm passing through a P.T.F.E. insulating plug in the wall of the vacuum vessel and connected

through this to the H.T. source. The grid covering the entrance aperture in the box had to be of two layers in order to provide adequate screening of the weak internal extraction field from the strong accelerating field outside and at the same time be of high transparency. The grid G2 is of similar construction, but G1 comprises only a single layer. All the grids are wound with inconel wire 0.025 mm in diameter with a quality of surface finish used in proportional counter construction. The pitch of each winding is 0.5 mm and the windings in both double layer grids are separated by 3 mm. G2 is mounted on an insulated frame but is maintained at earth potential during normal operation of the detector. In subsidiary measurements it could be used, in conjunction with G1, to apply a repelling field to the incident ions.

For the purpose of testing the detector an ion gun, also shown in fig. 1, was constructed to provide a pencil beam of Li^+ ions whose energy could be controlled up to 2 keV. Lithium was chosen since the process to be studied was the decay $^6\text{He} \rightarrow \text{Li}^6$. The ions are emitted from a directly heated platinum wire coated with $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ prepared according to the recipe of Blewett and Jones⁹). To assist in obtaining a beam current independent of ion energy, the ions are accelerated in two stages. A small constant potential is applied between the emitter and an intermediate cylindrical electrode surrounding it, and a further variable potential applied between this and a concentric outer cylinder at earth. Ions penetrate the intermediate electrode through a hole 2 mm in diameter, covered with silver gauze with 160 lines per cm to reduce focusing effects, and the diameter of the emerging beam defined by a 0.6 mm hole in the outer cylinder. The gun can be rotated about a vertical axis from outside the vacuum system and the beam deflected vertically with a pair of electrostatic deflecting plates, thus enabling the whole of the detector aperture to be scanned.

3. Performance of the Detector

The performance of the detector was investigated only so far as was necessary to determine its suitability.

⁸) N. R. Daly, Rev. Sci. Instr. 31 (1960) 264.

⁹) J. P. Blewett and E. J. Jones, Phys. Rev. 50 (1936) 464.

bility for the He^6 recoil work. Of particular importance were 1. an accurate calibration of detection efficiency versus incident ion energy, and 2. the establishing of a uniform detection efficiency over the entire input aperture.

In a preliminary run, pulse amplitude distributions from the photomultiplier were measured with a 100 channel analyser for a variety of accelerating

pulses fail to be registered. The background itself was due almost entirely to photomultiplier noise since it persisted when the H.T. supply to the box was cut off. Scrupulous attention however had to be paid to excluding dust during assembly and on occasion very high backgrounds were observed due to its presence.

Fig. 3 shows the counting rate observed as

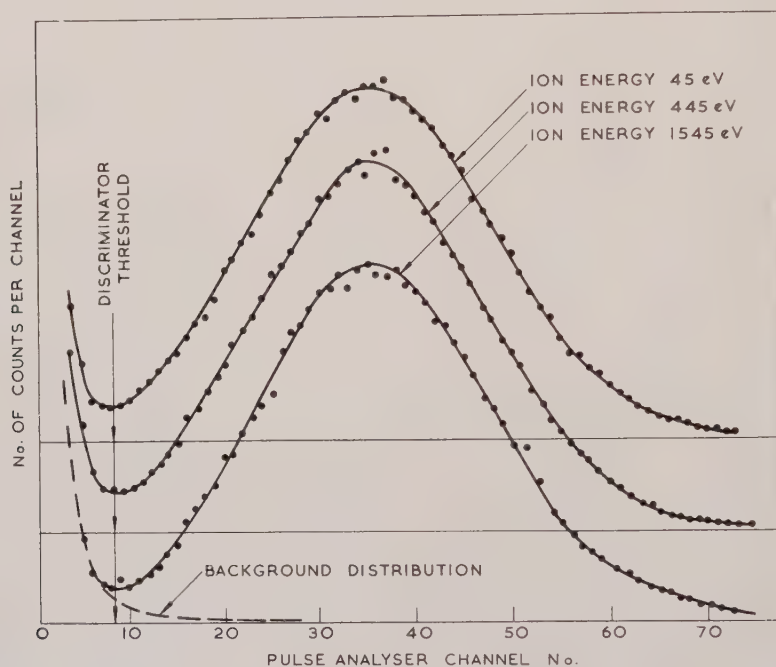


Fig. 2. Pulse amplitude distributions from Li^+ ions of various incident energies. The potential of the detector box was 11.5 kV in all cases.

potentials in the ion gun. Fig. 2 shows three of these, measured with ions of energy 45 eV, 445 eV and 1545 eV respectively. A comparison with the pulse amplitude obtained on irradiating the phosphor with 626 keV electrons from a Cs^{137} source showed that the mean total energy of secondary electron showers entering the phosphor was 70 keV, assuming a linear relation between phosphor light output and electron energy. This implies that an average of about 6 secondary electrons were produced per ion incident on the Be-Cu surface.

The background pulse distribution is indicated by the dotted line in fig. 2, and the counting rate above an amplitude indicated by the arrow was 0.3 counts per sec. With a discriminator set at this level it is estimated that less than 1% of genuine ion

function of ion energy for a nominally constant ion current. In these measurements the detected signals were registered by a scaler with discriminator threshold corresponding with the arrow in fig. 2. The observed variation cannot be attributed to a change in gain at the primary multiplying surface in view of the similarity between pulse amplitude spectra at different energies shown in fig. 2. A possible explanation may however lie in a variation with ion energy of the transparency of the earth grids before the detector. This argument is illustrated in fig. 4 and confirmed by a rough calculation which suggests that the transparency of the right hand layer of G2 would vary from 100% for zero energy ions to the geometrical shadow value of 95% at a few keV. A practical difficulty

es in distinguishing real changes in detector efficiency from variations of the ion current with accelerating conditions in the gun. Effects in the gun

current and therefore that the observed variation in counting rate is due wholly to the detector. The relatively greater counting rate for high second

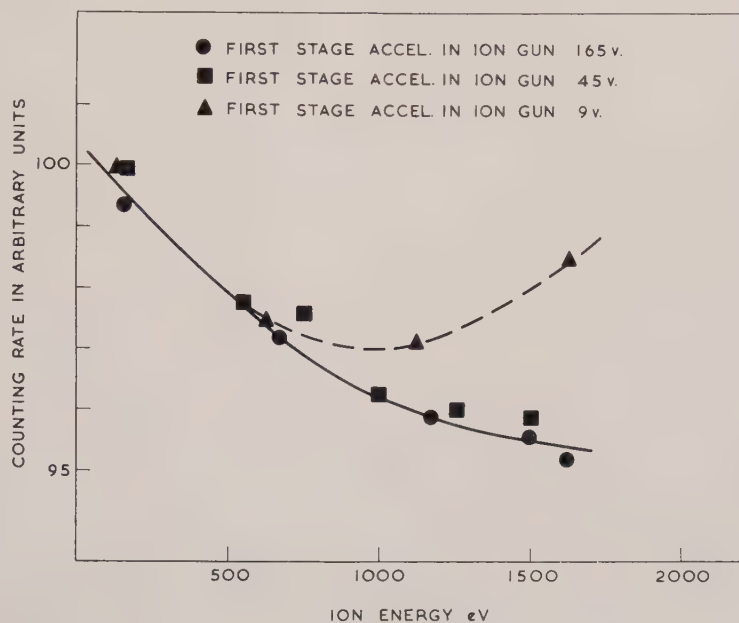


Fig. 3. Counting rate as function of ion energy for nominally constant ion current.

self would be expected to depend only on the ratio of potentials in the two stages of acceleration. For this reason, three separate runs were made in which the accelerating potentials between the ion emitter and intermediate electrode were 9 V, 45 V

stage accelerating potentials in the gun when the first stage potential is 9 V would be expected from an increasing transparency of the gauge covered aperture in the intermediate electrode.

The results described above were obtained directing the ion beam into the centre of the detector aperture. The counting rate observed as a function of beam position in a horizontal scan across the aperture is shown in fig. 5. The profile at the edge is consistent with the expected beam width, and the pulse amplitude distribution observed with the beam directed to give half maximum counting rate confirmed that the fall off was not due to a change in gain. Further measurements using vertical deflection confirmed that the detection efficiency was uniformly maintained over the entire aperture.

In an investigation of aging effects the pulse amplitude distribution was observed at intervals over a period of 30 hours following evacuation of the system after exposure to atmosphere. No significant variation was found.

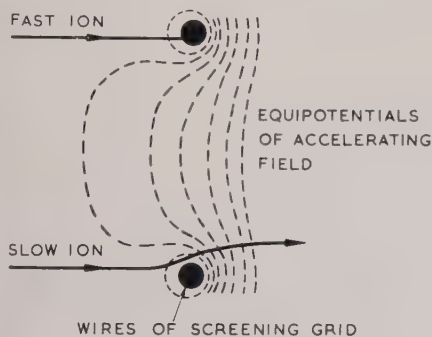


Fig. 4. Illustration of energy dependence of grid transparency. Fast ions hit the grid wires whereas slow ions are deflected round them by the penetrating field.

and 165 V respectively. The agreement between guns at 45 V and 165 V suggests that under these conditions the gun is delivering a constant ion

4. Conclusions

The combination of a single stage electron multiplier with a scintillation counter to detect secondary

Linear dimensional scaling of the detector should enable one of substantially larger aperture to be constructed, still using a 44 mm diameter phot

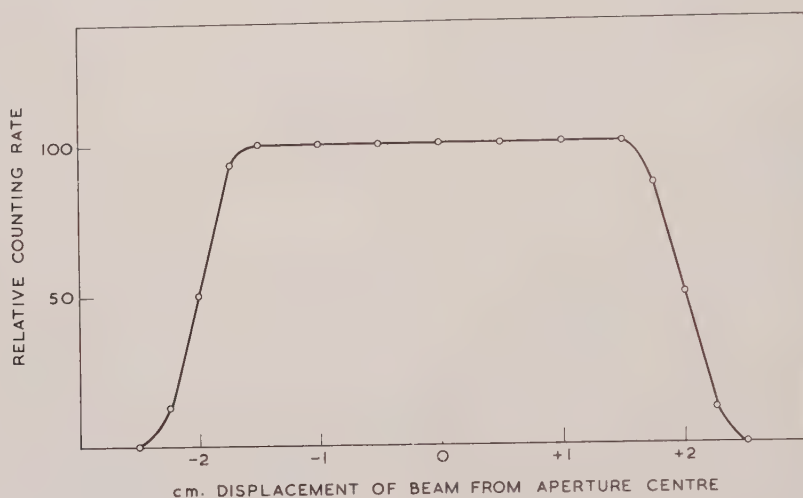


Fig. 5. Counting rate versus position of beam in a horizontal scan across the detector aperture.

electrons provides an efficient means for detecting slow positive ions over a wide energy range. The efficiency is uniformly maintained over an aperture 4 cm in diameter. A background counting rate as low as 0.3 counts per sec may be obtained with a discriminator threshold adjusted to accept 99% of pulses arising from ions. A variation in detector efficiency of a few per cent over the energy range 50 to 1500 eV is attributed to a transmission effect in the screening grids.

multiplier tube. However, it cannot easily be adapted to detect negative ions.

Acknowledgements

I should like to thank Dr. E. Bretscher and Dr. P. E. Cavanagh for their support in this work and Dr. Cavanagh and other members of his group for helpful discussions. The apparatus was constructed by Mr. M. E. Young and the beryllium-copper electrode prepared by Mr. D. W. S. Smo

LETTER TO THE EDITOR

CONSEQUENCES PRATIQUES DE L'INFLUENCE DE LA RÉSISTANCE DE CHARGE SUR L'EFFET
"COURONNE" DANS LES DETECTEURS À ÉTINCELLES DU TYPE (FILS-PLAN)

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Centre de Physique Nucléaire de la Faculté des Sciences, Toulouse, France

Reçu le 17 Octobre 1961

Introduction

Autour du fil anodique des compteurs à étincelles se produit une décharge par "effet couronne" qui conditionne la stabilité de comptage du détecteur¹⁾. D'une façon très générale, la courbe du courant de l'effet couronne en fonction de la tension a une pente positive: s'il n'en était pas ainsi, la décharge serait instable et le détecteur ne présenterait sans doute pas de plateau; ce fait est traduit quantitativement par la relation de Townsend:

$$I = KV(V - V_0)$$

I étant le courant total de l'effet couronne,
 V la tension aux bornes des électrodes,
 V_0 le seuil de l'effet couronne,
 K une constante dépendant du remplissage gazeux et des conditions géométriques.

Etablie théoriquement dans le cas de cylindres coaxiaux, cette relation garde la même forme lorsque la cathode est plane et que l'anode est un cylindre de petit diamètre, de longueur l . Nous posons $K = kl$; la décharge est entièrement définie par la tension V , ou par le courant (I/l) par unité de longueur du fil, et non par le courant total de l'effet couronne. Les propriétés du compteur à étincelles dépendent de ces mêmes paramètres.

Rôle de la résistance de charge

Supposons que l'on place en série avec le fil anodique une résistance R , la haute tension d'alimentation étant de E volts. L'application de la loi d'Ohm donne I et V en fonction de E :

$$\begin{cases} I = \frac{1}{2KR^2} - \frac{V_0}{2R} + \frac{E}{R} - \left[\left(\frac{1}{2KR^2} - \frac{V_0}{2R} \right)^2 + \frac{E}{KR^3} \right]^{\frac{1}{2}} \\ V = \frac{V_0}{2} - \frac{1}{2KR} + \left[\left(\frac{1}{2KR} - \frac{V_0}{2} \right)^2 + \frac{E}{KR} \right]^{\frac{1}{2}} \end{cases}$$

d'où

$$\begin{cases} \frac{I}{l} = \frac{1}{2kl^2R^2} - \frac{V_0}{2Rl} + \frac{E}{Rl} - \left[\left(\frac{1}{2kl^2R^2} - \frac{V_0}{2Rl} \right)^2 + \frac{E}{kl^3R^3} \right]^{\frac{1}{2}} \\ V = \frac{V_0}{2} - \frac{1}{2klR} + \left[\left(\frac{1}{2klR} - \frac{V_0}{2} \right)^2 + \frac{E}{klR} \right]^{\frac{1}{2}} \end{cases}$$

La résistance R a pour rôle de "stabiliser" la tension V ; la caractéristique $I(V)$ ayant une pente positive, V est une fonction croissante de E . Augmenter R revient à dilater selon les abscisses le début de la caractéristique de comptage tracée en fonction de E , comme cela a déjà été mis en évidence²⁾.

On remarquera que le produit ($l \times R$) figure aux dénominateurs des relations données ci-dessus: augmenter l a le même effet qu'accroître R . Nous avons vérifié ce point sur un détecteur à un fil, de construction analogue à celui décrit par Chang et Rosenblum³⁾ (diamètre du fil: 0.05 mm, distance fil-plan: 1 mm), branché sur une résistance de charge constante $R = 5$ mégohms, mais dont la longueur l pouvait prendre les valeurs: 2, 4, 6 et

¹⁾ D. Blanc, Journ. Phys. Radium 15 (1954) 483.

²⁾ E. Andreeshev et V. M. Isaev, Journ. Exp. Theor. Phys. USSR 28 (1955) 335.

³⁾ W. Y. Chang et S. Rosenblum, Phys. Rev. 67 (1945) 222.

9 cm. La figure 1 donne la variation de (I/l) en fonction de V , pour une haute tension E allant jusqu'à 5000 volts.

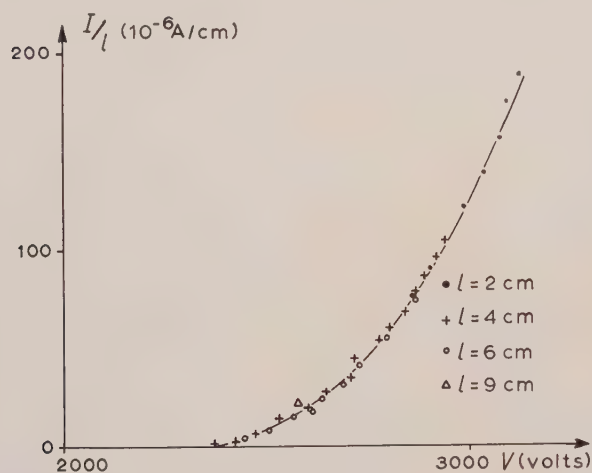


Fig. 1. Intensité de l'effet couronne par unité de longueur d'un compteur à fil, en fonction de la tension aux bornes des électrodes.

3. Conséquences concernant le montage électrique des détecteurs

Pour une valeur donnée de E , V et (I/l) sont déterminées par le produit $(l \times R)$: la valeur de la résistance de charge doit être choisie en fonction de

la longueur du compteur; elle doit, autant que possible, être inversement proportionnelle à l .

L'application de ce résultat aux compteurs à plusieurs fils est immédiate: soit un compteur à n fils, de longueur l , qui fonctionne correctement à l'aide d'un circuit de constante de temps $(\gamma + c)$, γ étant la capacité d'un condensateur placé en parallèle avec R , c la capacité propre du détecteur (c est proportionnelle à l). On pourra relier à la même haute tension E n compteurs identiques au précédent, sans que rien ne soit modifié, et obtenir ainsi un détecteur (A) à n fils.

On pourra encore relier les n fils à une résistance commune de valeur R/n , placée en parallèle avec un condensateur de capacité $n\gamma$ et réaliser un détecteur (B) à n fils.

Le détecteur (B) semble identique à (A): en réalité son temps de résolution est n fois plus grand que celui de (A), à cause de l'indépendance des fils de (A). De plus, en raison de sa faible résistance de charge (B) est moins stable que (A), l'arc, amorçant plus facilement; enfin (B), qui possède une forte capacité de coupure, délivrera des étincelles assez puissantes pour provoquer une détérioration rapide des électrodes. Dans toutes les applications on aura avantage à adopter le montage (A).

NEWS ITEM

INTERNATIONAL CONFERENCE ON SECTOR-FOCUSED CYCLOTRONS†

University of California, Los Angeles, 17–20 April 1962.

This conference is sponsored by the International Union of Pure and Applied Physics and the University of California. The purpose of the conference is to allow an exchange of information on the operating characteristics of several recently completed machines, to facilitate the exchange of information groups which are interested in "meson factories", and to aid groups which are considering the acquisition of cyclotrons to evaluate the scope and the cost of such a program. Attendance of any interested scientist is invited.

The program, except for one session on meson factories, will consist entirely of contributed papers. In broad outline it will be arranged as follows:

April 17 – Tuesday

Contributed papers on operational characteristics and/or unusual or unique features of design (including radiofrequency systems and methods of realization of required magnetic fields).

April 18 and 19 – Wednesday and Thursday

Contributed papers on orbit theory, magnetic field design, computer programs, starting conditions, beam extraction, beam quality, beam transport, sector-focused microtrons, magnetic field measuring techniques, and other relevant topics.

April 20 – Friday

Meson Factories

Requirements for Certain Meson Physics Experiments — R.P. Haddock, UCLA.

Comparison of Accelerator Types—Lloyd Smith, LRL.

Shielding and Activation Considerations—Burton J. Moyer, LRL.

Conceptual Design of a High Energy Cyclotron I—J.P. Blaser, ETH.

Conceptual Design of a High Energy Cyclotron II—P. Lapostolle, CERN.

Contributed papers on this topic.

Plans for publication of the *Proceedings* are as follows. The contributors will be required to arrive at the conference with their papers in final form, ready for immediate delivery to the second bulletin

editors (F. T. Howard, Oak Ridge National Laboratory and Kai Siegbahn, University of Uppsala). Only discussion originating from the floor will be recorded by a stenotypist. The editors will have the responsibility of boiling down the discussion and preparing it for publication. The entire manuscript will then be forwarded to North-Holland Publishing Company to appear as an issue of *Nuclear Instruments and Methods*. This plan will assure prompt publication of the *Proceedings*. Contributors will receive 25 complimentary reprints of each contribution and they can order additional copies at cost.

Contributions of two types are solicited, namely, A for oral presentation and publication, and B for publication only. It is unlikely that it will be possible to fit all the proposed type A contributions into the available time. So some of this type will have to be accepted for publication only. Type B contributions are intended to include electrical or mechanical details which are of value to the design of machines, but which the contributor recognizes as not being of sufficient general interest to be presented orally at the conference.

Instructions for the preparation of manuscripts appear on the inside of the cover of each issue of *Nuclear Instruments and Methods*. The editors are asking for at least two copies of the text (in English) and one set of all figures used in slides.

Contributors are urged to bring preprints of their papers for distribution during the meeting.

The Organizing Committee has authorized a Local Committee to arrange the program. The selection of papers to be presented orally will be made on the basis of abstracts of intended contributions. These abstracts (in English) should be no longer than approximately 200 words.

Delegates will be housed and have most of their meals in Mira Hershey Hall on the UCLA campus. The scientific sessions will be held in a nearby lecture hall in the Chemistry-Geology building. Cost of rooms and meals will be less than \$ 13 per day. One of the Thursday sessions may be held in the evening, leaving the afternoon free for an outing (most likely not as a single group).

Attention is called to the fact that the Spring meeting of the American Physical Society will be held in Washington, D.C., April 23–26, the week following our conference.

The next bulletin will be mailed about March 10 to all who have returned Registration Forms. It will contain some detailed information on the Program, a list of delegates, details concerning housing, and other items.

The following are members of the Organizing Committee:

- F. A. HEYN, Technical University, Delft.
- D. L. JUDD, Lawrence Radiation Laboratory, Berkeley.
- R. S. LIVINGSTON, Oak Ridge National Laboratory.
- K. R. MACKENZIE, University of California, Los Angeles.
- J. R. RICHARDSON, University of California, Los Angeles.
- B. T. WRIGHT, University of California, Los Angeles, Chairman.

BOOK REVIEWS

CONTROL OF NUCLEAR REACTORS AND POWER PLANTS by M. A. Schultz, second edition, 462 pages 331 figures, (McGraw-Hill Book Company, Inc. New York, Toronto, London) Price 97 s.

The first edition of this well known book was issued 1955 and has since been regarded as the classical text book in reactor control. However, in 1955 no civilian power plants were in operation and naturally to the author, being concerned with the U.S. naval program, the control problems were treated in the light of the Nautilus reactor.

This second edition has a much wider scope and is based on research, development and experience from the most fruitful six years of nuclear age. The 14 chapters of the book contains Elementary Physics of Reactor Control, Elementary Servo Mechanisms, Reactor Kinetics, The Reactor as a Control Element, Automatic Reactor Control, Reactor Control Mechanisms, Nuclear Power Plant Control, Boiling Reactor Plants, Reactor Control Radiation Detectors, Operational Control Problems at Startup, Power Operation and Shut Down and finally Simulators.

The new chapter on servo mechanisms presents a very good introduction into the fundamentals of the Laplace transform and transfer function with examples from other fields as a comparison. The stability criteria are formulated and the important Nyquist plot is treated. This chapter is the basis for the next chapter on Reactor Kinetics which presents transfer function derivations for several different reactor types. An interesting graphical method of solving ramp input reactivity problems was presented at the Geneva Conference 1958 and is described here.

In the chapter on the reactor as a control element is treated not only the moderator temperature coefficient but even the important fuel temperature coefficient due to the Doppler

broadening. The pressurized light water reactor is thoroughly covered but boiling water reactors, fast breeders and circulating fuel reactors are treated as well.

The description of control mechanisms covers a wide range of reactor types from fast breeders to the British gas cooled reactors.

This book is recommended to everyone who is concerned with reactor control design and reactor operation. It contains more than 500 references and is thus useful to those who wish to go into further detail.

MATTS STRAND

CARBON-14 COMPOUNDS by J. R. Catch (Butterworths, London 1961) p. 128, 30s.

This book deals with problems in connection with handling carbon-14 compounds. The production of carbon-14, synthesis, labelling, special peculiar features of carbon-14 compounds, analysis, measurement and precautions are treated. The author's intention was to write short reviews over the mentioned problems. This book is a very good and useful guide to the literature and will surely help especially the newcomer.

Present practice is to extract the carbon produced according to $^{14}_7\text{N} (n, p) ^{14}_6\text{C}$ by complete oxidation to carbon dioxide. The best isotopic abundances now approach 80 per cent. CO_2 is usually stored and distributed as metallic carbonate and the organic compounds are prepared by chemical and biological synthesis. The sample can be measured in solid, liquid or gas form with different methods as is described briefly.

It is of great importance that the precautions necessary are treated.

INGRID OLSSON

The Wave Mechanics of Electrons in Metals



S. Raimes

Imperial College, University of London

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